KINETICS OF BIOLOGICAL NITROGEN REMOVAL IN A SINGLE SLUDGE ACTIVATED SLUDGE PROCESS

by

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A thesis submitted in partial fulfilment of the requirements for the Degree of Master of Science in the Faculty of Engineering, University of Cape Town.

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August 1981

DECLARATION BY CANDIDATE

I, EPHRAIM SEHAYEK, hereby declare that this thesis is my own work and that it has not been submitted for a degree at another university.

Signed by candidate

August 1981

SYNOPSIS

The objective of this investigation was to develop experimental set-ups and operational procedures for accurate and reliable evaluation of the kinetic constants and sewage characteristics that influence nitrification and denitrification in the single sludge nitrification-denitrification activated sludge process. The kinetic constant that crucially affects nitrification has been identified as the maximum nitrification rate constant, μ_{nmT}; the kinetic constants and sewage characteristic that crucially affect denitrification are the substrate utilization rate constant for slowly biodegradable COD in an aerobic environment, K_{mpT}, the ratio of substrate utilization rate constant for slowly biodegradable COD in an anoxic environment to that in an aerobic environment, $\eta = K'_{mpT}/K_{mpT}$ and the ratio of easily to total biodegradable COD in the influent, f_{ca}, respectively.

Series reactor systems under cyclic flow and load had previously been used extensively by Van Haandel, Ekama and Marais to determine the constants above by calibration. With this operational set up the main problem encountered was that the combination of series configuration *together* with cyclic flow and load led to an unstable response in a particular reactor so that it was not suitable for accurate evaluations by calibration. A refinement, using a series reactor system under constant flow and COD load and imposing *cyclic TKN load* indicated a practical problem: extremely accurate metering of the TKN pulse feeding rate and the recycle rates is required to obtain reliable estimates of the kinetic constants (by calibration against the general dynamic steady state model). This accuracy was not obtainable with the pumps available giving rise to imprecise and inaccurate evaluations.

To overcome the problems set out above a constant flow completely mixed *single* reactor system was proposed to be operated under a sequence of anoxic and aerobic periods. Application of the general dynamic steady state program to this system required extension of the program to accommodate the sequential anoxic aerobic operating condition. The approach proved singularly successful: the experimental data showed stable reproducibility and the general

dynamic steady state model simulated the response under constant flow and load very successfully to allow precise evaluation of the constants by calibration. This was found to be the case also, but to a lower degree of precision, for square wave flow and load conditions with anoxic aerobic sequences superimposed. One problem encountered was to simulate closely the response when (as was often the case) the experiment was performed on a day when the influent characteristics (TKN/COD ratio and COD) deviated appreciably from the mean values for the antecedent days. In this situation a satisfactory solution was to use the simulated data from the dynamic steady state program as initial input to commence the simulation for the particular day over which the experiment was performed with its particular influent flow and load. By this means the constants could still be evaluated with precision.

A useful development was that it was found possible to *manually* calculate μ_{nmT} from the experimental nitrate response of the system with good accuracy. The denitrification kinetic constants, K_{mpT} and η, could also be manually determined *provided* the operational conditions were such that the concentration of the stored COD mass, X_s, remained high.

Evaluation of the denitrification kinetic constants requires knowledge of the easily biodegradable COD fraction in the influent waste, f_{ca}. The magnitude of f_{ca} was determined by an independent experimental set up as described by Ekama and Marais.

The various experiments undertaken in this investigation indicate that for different waste influents μ_{nm20} could vary from 0,33 to 0,60 [d^{-1}], f_{ca} from 0,10 to 0,20 [mg COD.mg COD^{-1}] and K_{mp20} from 2,3 to 3,0 [mg COD.mg $VSS^{-1}.d^{-1}$], possibly due to presence of varying industrial fractions in the respective influents. Variation in K_{mp20} has not such a marked effect on the simulations except at high anoxic sludge mass fractions but μ_{nmT} and f_{ca} are the parameters that crucially affect nitrification and denitrification respectively - accurate experimental estimation of μ_{nmT} and f_{ca}, using the proposed influent waste as feed source is essential therefore for meaningful predictions of nitrification and denitrification behaviour in any anoxic-aerobic activated sludge process.

ACKNOWLEDGEMENTS

I wish to express my gratitude to the following:

Professor G v R Marais, Water Resources and Public Health Engineering, University of Cape Town, under whose supervision and guidance this research was undertaken. His guidance and astute advice at all times is greatly appreciated.

Mr R F Beverton, Senior Technician, Department of Civil Engineering, for the construction of the laboratory scale experimental units and prompt service in times of difficulties.

Mr A C van Haandel (M.Sc.)(Eng.) for his help and advice throughout this work, especially in the programming area.

Mr I Siebritz (B.Sc.)(Eng.), for his practical advice and encouragement when disappointments were encountered.

Messrs T Lakay and J George, for cheerful assistance throughout the period of this investigation.

Finally, Mrs Bain who patiently typed the script.

LIST OF CONTENTS

LIST OF SYMBOLS

SYMBOL	DESCRIPTION
a	Mixed liquor recycle ratio from an aerobic to a predenitrification reactor.
b_h	Endogenous respiration rate constant for active sludge [d^{-1}].
b'_h	Death rate constant for active sludge [d^{-1}].
b_n	Death rate constant for nitrifiers [d^{-1}].
f	Inert residue in the endogenous respiration approach.
f'	Inert residue in the death regeneration approach.
f_{ca}	Ratio of easily to total biodegradable material in the influent.
f_{ma}	Maximum fraction of substrate that can be stored on the active sites. (Maximum ratio of stored material/active sludge).
f_n	Mass fraction of nitrogen in the organic sludge [mg N.mg VSS^{-1}].
f_{na}	Ratio of ammonia to total TKN in the influent.
f_{ns}	Ratio of TKN to organic material in the stored material [mg N.mg COD^{-1}].
f_{nu}	Unbiodegradable soluble TKN fraction in the influent.
f_{up}	Unbiodegradable particulate influent COD fraction [mg VSS.mg COD^{-1}].
f_{us}	Unbiodegradable soluble influent COD fraction.
f_{xl}	Primary (predenitrification) anoxic sludge mass fraction.
f_{xm}	Maximum anoxic sludge mass fraction to allow stable nitrification.
f_{xt}	Total unaerated sludge mass fraction.

q	Volumetric wastage flow rate [$\ell.d^{-1}$].
r	General symbol indicating the rate of a particular mechanism or the reaction rate of one of the variables in the activated sludge process [$mg.\ell^{-1}.d^{-1}$] or [$mg.\ell^{-1}.h^{-1}$].
	index h refers to hydraulic rate index obs refers to observed rate index r refers to reaction rate.
s	Underflow recycle ratio.
t_a	Actual anoxic retention time [h].
t_f	Feeding period [h].
t_2-t_1	Time interval between any two moments [h].
Alk	Alkalinity expressed in ppm as $CaCO_3$.
C_c	Concentration of a variable C [$mg.\ell^{-1}$].
COD	Carbonaceous material concentration [mg COD.ℓ^{-1}].
D	Dissolved oxygen (D.O) concentration [mg O.ℓ^{-1}].
K	Empirical denitrification rate constant [mg N.mg $VSS^{-1}.h^{-1}$] or [mg N.mg $VSS^{-1}.d^{-1}$].
K_1	High rate (primary phase) predenitrification rate constant [mg N.mg $VSS^{-1}.h^{-1}$] or [mg N.mg $VSS^{-1}.d^{-1}$].
K_2	Low rate (secondary phase) predenitrification rate constant [mg N.mg $VSS^{-1}.h^{-1}$] or [mg N.mg $VSS^{-1}.d^{-1}$].
K_3	Low rate post-denitrification rate constant [mg N.mg $VSS^{-1}.h^{-1}$] or [mg N.mg $VSS^{-1}.d^{-1}$].
K_{mp}	Substrate utilization rate constant for slowly biodegradable COD in an aerobic environment [mg COD.mg $VSS^{-1}.d^{-1}$].
K'_{mp}	Substrate utilization rate constant for slowly biodegradable COD in an anoxic environment [mg COD.mg $VSS^{-1}.d^{-1}$].
K_{ms}	Substrate utilization rate constant for easily biodegradable COD [mg COD.mg $VSS^{-1}.d^{-1}$].
K_n	Half saturation value for nitrification [mg NH_3-N.ℓ^{-1}].
K_r	Conversion rate constant for organic nitrogen [ℓ.mg $VSS^{-1}.d^{-1}$].

K_{sp} Half saturation value for slowly biodegradable COD (active site approach) [mg COD.mg VSS^{-1}].

K_{ss} Half saturation value for easily biodegradable COD [mg COD.ℓ^{-1}].

K_v Adsorption rate constant for adsorption of particulate biodegradable material [ℓ.mg $VSS^{-1}.d^{-1}$].

M(X) Mass of sludge present in an activated sludge system [mg VSS].

index a refers to active sludge
index n refers to nitrifiers
index v refers to volatile solids
index x refers to any parameter.

N_a or NH_3 Ammonia concentration [mg NH_3-N.ℓ^{-1}].

N_{ae} Effluent ammonia concentration [mg NH_3-N.ℓ^{-1}].

NON Organic nitrogen concentration [mg NON-N.ℓ^{-1}].

N_n or NO_3 Nitrate concentration [mg NO_3-N.ℓ^{-1}]

N_s Heterotrophic nutrient nitrogen requirement [mg N.ℓ^{-1}].

O General symbol denoting oxygen uptake rate in an aerobic reactor [mg O.$\ell^{-1}.h^{-1}$].

index c refers to oxygen uptake rate associated with oxidation of carbonaceous material.
index n refers to oxygen uptake rate associated with oxidation of ammonia.
index sbp refers to oxygen uptake rate associated with oxidation of slowly biodegradable COD.
index sbs refers to oxygen uptake rate associated with oxidation of easily biodegradable COD.
index t refers to total oxygen uptake rate.

P COD equivalence of organic sludge = COD/VSS ratio [mg COD.mg VSS^{-1}].

Q General symbol indicating flow rate [$\ell.d^{-1}$]
index a refers to actual flow rate
index b refers to base flow rate.

K_{sp} Half saturation value for slowly biodegradable COD (active site approach) [mg COD.mg VSS^{-1}].

K_{ss} Half saturation value for easily biodegradable COD [mg COD.ℓ^{-1}].

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P COD equivalence of organic sludge = COD/VSS ratio [mg COD.mg VSS^{-1}].

Q General symbol indicating flow rate [$\ell.d^{-1}$]

index a refers to actual flow rate
index b refers to base flow rate.

R_h Hydraulic (nominal,unless otherwise stated) retention time [d].

R_s Sludge age [d].

R_{sm} Minimum sludge age required for nitrification [d].

R_o Nominal retention time during which the high rate (primary phase) predenitrification rate constant, K_{1T} is operative [d].

R_1 Total nominal retention time in the predenitrification reactor [d].

R_3 Nominal retention time in the post-denitrification reactor [d].

S General symbol indicating COD substrate [mg COD.ℓ^{-1}].

index b refers to biodegradable substrate.
index bp refers to slowly biodegradable substrate.
index bs refers to easily biodegradable substrate
index t refers to total carbonaceous material
index u refers to unbiodegradable soluble COD.

S_f Factor of safety introduced to ensure efficient nitrification.

TKN Total kjeldahl nitrogen concentration [mg N.ℓ^{-1}].

V Total reactor volume [ℓ].

VSS Volatile suspended solids concentration [mg VSS.ℓ^{-1}].

X General symbol indicating sludge concentration [mg VSS.ℓ^{-1}].

index a refers to active sludge
index e refers to endogenous residue
index i refers to inert material
index n refers to nitrifiers
index s refers to stored material
index v refers to volatile solids.

Y_h Yield coefficient of active heterotrophic sludge [mg VSS.mg COD^{-1}].

Y_n Yield coefficient of nitrifiers [mg VSS.mg N^{-1}].

α Proportionality constant between extent of high rate nitrate removal and influent biodegradable COD concentration = $f_{ca}(1-PY_h)/2,86$ [mg NO_3-N.mg COD^{-1}].

Δ	General symbol denoting a net change.
ΔN	Total nitrogen removal [mg NO_3-N.ℓ^{-1}].
ΔN_1 or ΔN_{sbs}	Nitrogen removed due to utilization of easily biodegradable COD in a predenitrification reactor [mg NO_3-N.ℓ^{-1}].
ΔN_2 or ΔN_{sbp}	Nitrogen removed due to utilization of slowly biodegradable COD in a predenitrification reactor [mg NO_3-N.ℓ^{-1}].
ΔN_3	Nitrogen removed due to utilization of particulate COD in a post-denitrification reactor [mg NO_3- N.ℓ^{-1}]
η	Ratio of substrate utilization constant for slowly biodegradable COD in an anoxic environment to that in an aerobic environment = K'_{mp}/K_{mp}.
μ_n	Specific growth rate of nitrifiers [d^{-1}].
μ_{nm}	Maximum specific growth rate of nitrifiers [d^{-1}].
μ'_{nm}	Effective maximum specific growth rate of nitrifiers [d^{-1}].

Suffixes to Subscripts

T	refers to temperature [°C].
i	refers to influent.
p	refers to peak value.

LIST OF TABLES

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* AAACMSRS = Alternating anoxic aerobic completely mixed single reactor system.

LIST OF FIGURES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Three nitrification-denitrification activated sludge systems have been developed; the three sludge, two sludge and single sludge system, respectively. In the three sludge system the respective carbonaceous energy removal, nitrification and denitrification phases are achieved by having three separate reactor systems each with a settler (Fig.1a). Denitrification is achieved by adding an external energy source typically methanol, to the third reactor, this reactor being maintained in an anoxic state. In the two sludge system the energy removal and nitrification phases are consolidated to take place in *one* reactor and that of denitrification in a second, each with a separate settler (Fig.1b). In the single sludge process aerobic energy removal, nitrification and denitrification are mediated by the same sludge mass in a series reactor system having aerated and unaerated reactors (Fig.1c), or in a single reactor which is sequentially made aerobic and anoxic. The energy source for denitrification in the single sludge process is the organic material in the influent.

The three and two sludge systems have not been applied extensively in practice even though theoretically they are competent systems, the main reason against their use being the high cost of the energy source (usually methanol) for denitrification. As a consequence the single sludge system has received extensive attention as an alternative to the three and two sludge systems.

Modelling of the *three* sludge system has been accomplished relatively easily because the carbonaceous energy removal, nitrification and denitrification respectively, take place in separate reactors. Modelling of the *two* sludge system, where energy removal and nitrification occur in the first reactor, also has not presented any serious difficulties, the reason for this being that the energy removal and nitrification reactions are mediated by two entirely different groups of organisms - the autotrophic nitrifiers and heterotrophic energy removers - their respective kinetic behaviour in the same reactor can be modelled virtually independently of each

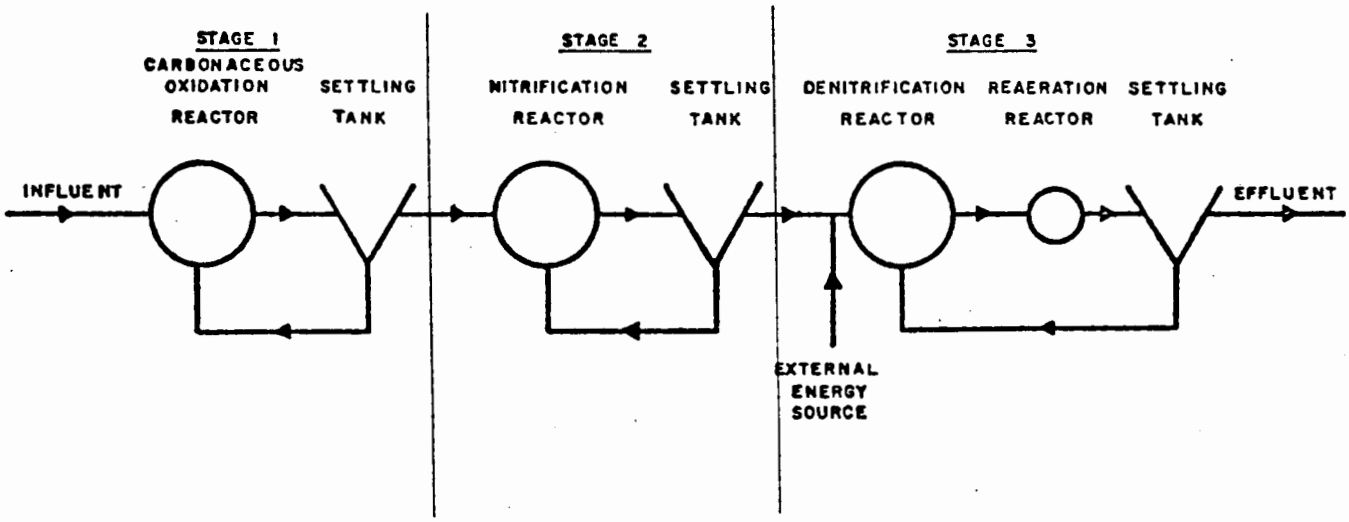

Fig.1a: Three sludge systems for denitrification with an external energy source.

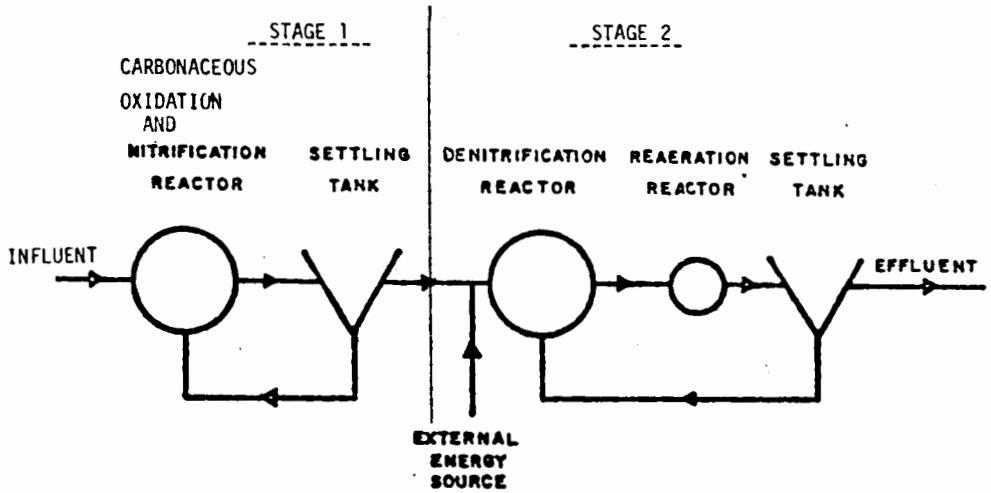

Fig.1b: Two sludge systems for denitrification with an external energy source.

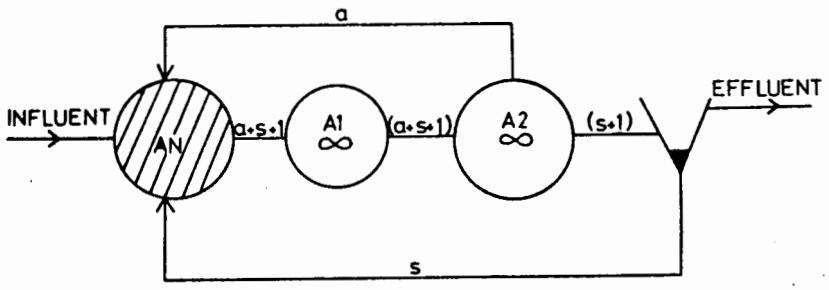

Fig.1c: Single sludge predenitrification series reactor system.

other; the two reactions are linked only insofar as the reactor and the process parameters (sludge age, temperature) are common to both, and that ammonia is abstracted from the wastewater for growth by both groups of organisms.

The denitrification phase in both the three and two sludge systems is entirely divorced from the preceding energy removal and nitrification phases. In addition, as the energy source for denitrification is very specific (say methanol), the organism type that develops in the denitrification reactor is also very specific to the energy source (as an electron donor) and nitrate (as an electron acceptor).

In contrast to the two and three sludge systems, modelling of the single sludge process requires description of a complex system of interacting reactions: energy removal for heterotrophic growth takes place from the same substrate source under sequential aerobic and anoxic (denitrification) phases, by the *same* organism mass; nitrification is affected by anoxic conditions in that growth of nitrifiers can take place only in an aerobic environment, but endogenous respiration takes place under both aerobic and anoxic conditions, and so on. Despite the complexity of the behaviour of the single sludge nitrification-denitrification process, because denitrification, like aerobic energy removal, is mediated by heterotrophic facultative organisms, Van Haandel, Ekama and Marais (1981) found that response of the autotrophs in an anoxic state may be described by the general model for aerobic systems developed by Dold, Ekama and Marais (1980), if it is assumed that only about 40% of the heterotrophs can utilize nitrate instead of oxygen as an electron acceptor. With this assumption they obtained very good correlation between the theoretically predicted and observed response at 20°C.

Accepting the basic model of Van Haandel *et al*, accurate description of the processes depends, *inter alia*, on the values assigned to the kinetic constants and sewage characteristics. These are determined by calibration of the model against response data. Because of the large number of parameters involved in the general model, it is possible to simulate satisfactorily the experimentally

observed data using different sets of constants, the reason for this being that some of the constants tend to act in a compensatory fashion with others. Assignment of precise values to the constants therefore requires *inter alia* experimental set ups that have good descriminative power for the particular constants to be evaluated. To obtain this descrimination, generally it is necessary to induce transient states in the system. Up to the present, this has been obtained by setting up series systems having anoxic and aerobic reactors operated under cyclic (usually square wave) flow and load conditions. Intrinsic to this system are the recycles to supply the mixed liquor and nitrate to the appropriate reactors. With this operational set up it has been found that the combination of series configuration, cyclic flow and load and recycles causes unstable response in a particular reactor and in consequence this approach has not been as successful as originally hoped in obtaining precise and accurate evaluations of constants by calibration.

The lack of precision and accuracy has provided the incentive to seek alternative set-ups and operational procedures to achieve estimates of greater reliability. For example, if the series configuration is selected such that a very short retention time is present in a particular reactor, so short that the reaction of interest is not complete, a transient type situation will be induced and the need for a cyclic flow and load might be eliminated and this cause for instability removed. Alternatively a *single* reactor might be operated under a time sequence of aerobic and anoxic conditions under constant or cyclic flow and load conditions. In such a system transients will be induced every time the operation is changed from aerobic to anoxic. A single reactor system also will not be affected by recycles as the recycle, in effect, is intra reactor.

This report describes the research conducted into the development of different experimental set ups and operational procedures in the search for accurate and reliable evaluations of the kinetic constants and the sewage characteristics that influence nitrification and denitrification in single sludge systems.

CHAPTER 2

LITERATURE REVIEW

2.1 Autotrophic Nitrification

2.1.1 Stoichiometry of nitrification

In biological nitrification oxidation of ammonia to nitrate is mediated by autotrophic bacteria and takes place in two steps. The first oxidation step, which yields nitrite, is mediated by autotroph *Nitrosomonas* (sp). Stoichiometrically:

$$NH_4^+ + 3/2\ O_2 \xrightarrow{Nitrosomonas} 2H^+ + H_2O + NO_2^- \qquad (2.1.1)$$

and the second oxidation step, which yields nitrate, is mediated by autotroph *Nitrobacter* (sp). Again stoichiometrically:

$$NO_2^- + 1/2\ O_2 \xrightarrow{Nitrobacter} NO_3^- \qquad (2.1.2)$$

The first step (Eq. 2.1.1) is the rate limiting one; nitrite is converted to nitrate almost as soon as it is formed. It is for this reason that most biologically nitrified ammonia is in the nitrate form. From a kinetic point of view the rate limiting step mediated by *Nitrosomonas*, therefore, becomes the step of importance. Hence the equivalent stoichiometric equation for conversion of ammonia to nitrate is written:

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O \qquad (2.2)$$

Considering the *Nitrosomonas*, Haug and McCarty (1971) accepted an empirical formula for the protoplasm of *Nitrosomonas* as $C_5H_7NO_2$. From reported data they selected a yield coefficient Y_n = 0,15 (mg VSS.mg N^{-1}) for autotrophic sludge production and apparently, using this yield coefficient it was possible to develop* the following

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* Haug *et al* (1971) do not set out exactly how Eq.(2.3) was developed. However, the production of 1 mole $C_5H_7NO_2$ (113 g) from 55 moles NH_4^+ (770 g-N) corresponds to a yield coefficient

Y_n = 113/770 = 0,15 (mg *Nitrosomonas*.mg N^{-1})

Nitrification of one mole of ammonia to nitrate produces 2 moles of H^+ (= 2g H^+) or equivalently consumes 2,50 = 100 g of alkalinity expressed as $CaCO_3$ (Loewenthal and Marais, 1976) i.e.

14 g N ≡ 2 g H^+ ≡ 100 g $CaCO_3$

or

1 mg N ≡ 7,14 mg $CaCO_3$

i.e. for each 1 mg of NH_4^+-N nitrified there is a consumption of 7,14 mg alkalinity expressed as $CaCO_3$.

2.1.3 Oxygen requirements of nitrification

Equation (2.2) describes the stoichiometric oxygen requirements for nitrification and states that nitrification of 1 mole of ammonia (= 14 g expressed as NH_4^+-N) to nitrate requires 2 moles of oxygen (= 64 g 0), i.e. the nitrification of 1 mg NH_4^+-N requires 64/14 = 4,57 mg 0.

2.2 Nitrification Kinetics

2.2.1 Nitrification kinetics in aerobic systems

Investigations of (Downing, Painter and Knowles, 1964) indicate that the relationship by Monod (1950) satisfactorily describes the rate of nitrification, i.e.

$$\mu_{nT} = \mu_{nmT} N_a/(N_a+K_{nT}) \qquad (2.4)$$

μ_{nT} = Specific growth rate of nitrifiers [d^{-1}]

μ_{nmT} = Maximum specific growth rate of nitrifiers [d^{-1}]

K_{nT} = Monod half saturation coefficient [mg NH_3-N.ℓ^{-1}]

N_a = Ammonia (substrate) concentration [mg NH_3-N.ℓ^{-1}]

The index 'T' refers to temperature [°C]

The basic equation for the rate of synthesis is given by:

$$dX_n/dt = \mu_{nT} X_n = (\mu_{nmT} N_a/(N_a+K_{nT}))X_n \qquad (2.5)$$

X_n = Concentration of nitrifiers [mg $X_n.\ell^{-1}$]

Now the mass of ammonia removed in relation to the mass of nitrifier synthesised is given by

$$\Delta X_n = Y_n \Delta N_a \qquad (2.6a)$$

where Y_n = Yield coefficient for nitrifiers [mg VSS.mg NH_3-N^{-1}]

Hence the rates can be expressed by

$$dX_n/dt = Y_n(dN_a/dt) \qquad (2.6b)$$

Substituting for dX_n/dt from Eq. (2.5) yields

$$\frac{dN_a}{dt} = -\left(\frac{\mu_{nmT}}{Y_n}\right).\frac{N_a}{N_a + K_{nT}}.\ X_n \qquad (2.7)$$

The death rate of nitrifiers is given by

$$dX_n/dt = -b_{nT}X_n$$

b_{nT} = Death rate constant for nitrifiers [d^{-1}]

2.2.2 Nitrification process kinetics

The process response depends on the hydraulic regime (plug flow or completely mixed) together with the basic kinetic reactions. Assuming nitrification in a completely mixed reactor under constant flow and load conditions (depicted by Fig. 2.1), a mass balance on the accumulation of nitrifier mass, $M(\Delta X_n)$ is given by

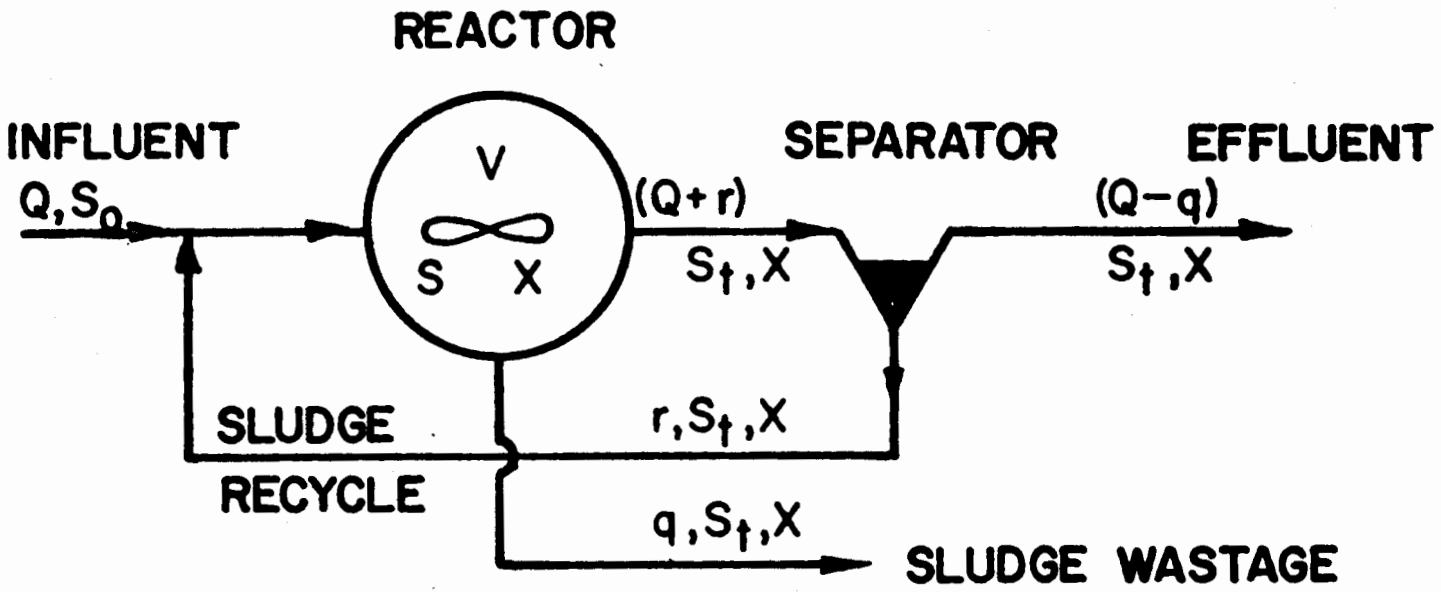
$$M(\Delta X_n) = V.\Delta X_n = [\mu_{nmT}.N_a/(N_a+K_{nT})].X_n.V.\Delta t - b_{nT}.X_n.V.\Delta t - X_n.q\Delta t$$

where

V = Process volume [ℓ]

q = Volumetric withdrawal rate of sludge *from the reactor* [$\ell.d^{-1}$]

Dividing through by $V.\Delta t$



COMPLETELY MIXED ACTIVATED SLUDGE PROCESS WITH RECYCLING

Fig.2.1: A diagrammatic representation of the completely mixed activated sludge process with hydraulic control of sludge age and sludge recycle.

$$\therefore \Delta X_n/\Delta t = [\mu_{nmT} N_a/(N_a+K_{nT})].X_n - b_{nT}X_n - X_n q/V \qquad (2.8a)$$

Now, $$\frac{VX_v}{qX_v} = \frac{\text{mass of sludge in the process per day}}{\text{mass of sludge wasted per day}} = \frac{V}{q}$$

$V/q = R_s$ defines the sludge age, R_s[d].

Under constant flow and load conditions eventually a steady state will be achieved when

$$dX_n/dt = 0$$

Equating Eq. (2.8a) to zero for steady state and substituting $1/R_s$ for q/V gives

$$[\mu_{nmT} N_a/(N_a+K_{nT})]X_n - b_{nT}X_n - X_n/R_s = dX_n/dt = 0 \qquad (2.8b)$$

From Eq. (2.8b) by solving for N_a, the ammonia concentration in a single completely mixed aerobic reactor under constant flow and load conditions is determined i.e.

$$N_{ae} = \frac{K_{nT}(b_{nT}+1/R_s)}{[\mu_{nmT} - (b_{nT}+1/R_s)]} \qquad (2.8)$$

where

N_{ae} = Effluent ammonia concentration [mg NH_3-N.ℓ^{-1}]

Equation (2.8) provides a basis for estimation of the minimum aerobic sludge age required for nitrification, R_{sm}, (i.e. the sludge age below which nitrification ceases). This will occur when the effluent ammonia concentration (N_{ae}) equals the influent ammonia concentration (N_{ai}), i.e. when $N_a = N_{ai}$. Substituting $N_a = N_{ai}$ and noting that $K_{nT} \simeq 1{,}0$ [mg N.ℓ^{-1}] and $N_{ai} > 20$ [mg N.ℓ^{-1}] i.e. $N_{ai} >> K_{nT}$, in which event $K_{nT}/N_{ai} \simeq 0$, Eq. (2.8) reduces to $[\mu_{nmT} - (b_{nT}+1/R_s)] = 0$ or

$$R_{sm} = 1/(\mu_{nmT} - b_{nT}) \qquad (2.8c)$$

To illustrate the effect of sludge age on N_{ae} a plot of N_{ae} vs. R_s is shown in Fig 2.2 a with $b_{n20} = 0{,}04$ [d^{-1}], $K_{n20} = 1{,}0$ [mg $N.\ell^{-1}$] for different values of μ_{nmT}. It may be noted that as R_s increases slightly higher than R_{sm} so the effluent ammonia concentration rapidly reduces to a small value. This behaviour has been repeatedly observed in practice - a plant usually either nitrifies almost completely or not at all.

2.2.2a Presence of an anoxic zone

If a fraction f_{xt} of the total sludge mass is unaerated (anoxic), a fraction $(1-f_{xt})$ is aerobic. The effect of the anoxic zone on nitrification can be explained by hypothesizing that endogenous respiration takes place throughout the aerated and unaerated zones whereas growth can take place only in the fraction of sludge mass that is aerated. A nitrifier mass balance gives Eq. (2.9) for the nitrification behaviour in a nitrification-denitrification process (Ekama, Van Haandel and Marais 1979) i.e.

$$N_{ae} = \frac{[K_{nT}(b_{nT} + 1/R_s)]}{[(1-f_{xt})\mu_{nmT} - (b_{nT}+1/R_s)]} \qquad (2.9)$$

Comparing Eq. (2.9) with the corresponding aerobic one [Eq. (2.8)], the presence of the anoxic sludge mass fraction, (f_{xt}) equivalently reduces the value of μ_{nmT} i.e.

$$\mu'_{nmT} = (1-f_{xt})\mu_{nmT}$$

μ'_{nmT} = Effective maximum specific growth rate [d^{-1}]

If f_{xt} is fixed then the minimum sludge age for unaerated-aerobic systems can be calculated by substituting R_{sm} for R_s, $N_{ae} = N_{ai}$ and hence $K_{nT}/N_{ai} \simeq 0$ in Eq. (2.9). Solving for R_{sm}, for any given f_{xt}, yields

$$R_{sm} = 1/(\mu'_{nmT}-b_{nT}) = 1/[\mu_{nmT}(1-f_{xt})-b_{nT}] \qquad (2.10a)$$

Conversely, if the sludge age is fixed, the maximum anoxic sludge mass fraction to allow nitrification (f_{xm}) can be calculated by substituting f_{xm} for f_{xt}, $N_{ae} = N_{ai}$ and hence $K_{nT}/N_{ai} \simeq 0$ in Eq. (2.9). Solving for f_{xm}, for any given R_s, yields:

$$f_{xm} = 1 - (b_{nT} + 1/R_s)/\mu_{nmT} \qquad (2.10b)$$

As stated previously, theoretically complete nitrification is achieved almost immediately R_s exceeds R_{sm} (see Fig. 2.2a) but clearly it is undesirable to operate at R_s close to R_{sm} as this may lead to unstable nitrification. It is necessary therefore to calculate a sludge age so much longer than the minimum in order that effluent ammonia concentration (N_{ae}) will always be low. In practice two factors influence the selection of the sludge age:

(1) μ_{nmT} tends to vary around the mean value. Consequently the sludge age should at least be larger than that indicated by μ'_{nmT} in Eq. (2.10a).

(2) Under cyclic load and flow conditions particularly the latter, the nitrification efficiency declines because during the high flow period the contact time with the nitrifiers is too short to allow complete nitrification.

In order to ensure that the mass of nitrifiers is sufficiently large to deal with the forementioned influences, the sludge age should be appreciably greater than the minimum. From simulations of nitrification systems, Ekama *et al* (1979) found that if R_s is at least 1,25 times R_{sm}, nitrification is virtually complete even under cyclic flow and load conditions. In the analysis above the same provision can be made by applying a factor of safety in the calculation of f_{xm}. This is accomplished by incorporating a factor of safety, S_f, in Eq. (2.10b) as follows:

$$f_{xm} \simeq 1 - S_f(b_{nT} + 1/R_s)/\mu_{nmT} \qquad (2.11a)$$

In Eq. (2.11a) the value of f_{xm} is subject to a restriction:

Arkley and Marais (1981) found that when f_{xm} exceeds 0,45 to 0,50, the settling characteristics of the sludge deteriorate to such an extent that the required size of settlers makes the plant uneconomical. Equation (2.11a), therefore, is subjected to the constraint that

$$f_{xm} < 0{,}50 \qquad (2.11b)$$

This restriction has important implications in the design of nitrification-denitrification systems; these will be dealt with in Section 2.3.4.

2.2.3 Choice of nitrification constants

In order to calculate the kinetic behaviour of nitrification it is necessary to determine the magnitudes of all the kinetic constants affecting nitrification i.e. Y_n, b_{nT}, K_{nT} and μ_{nmT}. Some of these do not have a significant effect on nitrification rate so that great accuracy in determining their magnitude is not important. A comparative study of the effect of each of these parameters on the nitrification behavioural pattern will indicate which of the constants needs to be evaluated with great accuracy and which not.

Downing *et al* (1964), Knowles, Downing and Barret (1965), Lijklema (1973), Gujer (1977) and Ekama and Marais (1978) reported various values for Y_n, b_{nT}, K_{nT} and μ_{nmT}. The range of values for each of the constants, respectively, is given in Table 2.1.

Table 2.1 *Ranges of values of nitrification constants*

Constant	Range	Units
Y_n	0,05-0,15	mg VSS.mg N^{-1}
b_{n20}	0,04-0,07	d^{-1}
K_{n20}	0,2 -1,0	mg $N.\ell^{-1}$
μ_{nmT}	0,33-0,65	d^{-1}

In order to investigate the influence of each of the constants individually, a set of average values is accepted as a standard for comparison and the effects of changing each of the constants, keeping the others at their standard value, are investigated.

2.2.3(a) The significance of Y_n in nitrification

Two aspects determine the significance of Y_n in nitrification, i.e. practical considerations and theoretical considerations.

2.2.3(a.1) Practical significance of Y_n in nitrification

In a typical domestic waste the ratio of the influent TKN/COD $\simeq$ 0,1 [mg N.mg COD^{-1}]. By applying TKN/COD = 0,1 and other typical domestic sewage and operational characteristics (given in Table 2.2) to the various formulations used by Marais and Ekama (1976) for a completely mixed reactor under steady state conditions of constant flow and load, it is possible to compare the mass of nitrifier that is produced relative to the total mass of sludge that is generated for a given sludge age; this is depicted in Fig. 2.2. From Fig. 2.2 it is apparent that X_n never constitutes more than 2 per cent of the total sludge and therefore from a practical point of view the evaluation of X_n is of no consequence. Hence from Eq. (2.6a) it follows that the evaluation of Y_n is also of no consequence.

Table 2.2 *Operational and sewage characteristics used in Fig. 2.2*

Operational Characteristics:	
T	= 12°C
R_h	= 1,0[d]
Sewage Characteristics:	
S_{ti}	= 600 [mg COD.ℓ^{-1}]
f_{up}	= 0,09 [mg VSS.mg COD^{-1}]
f_{us}	= 0,05 [mg COD.mg COD^{-1}]
f_{nu}	= 0,0 [mg N.mg N^{-1}]
f_{na}	= 0,75 [mg NH_3-N.mg N^{-1}]

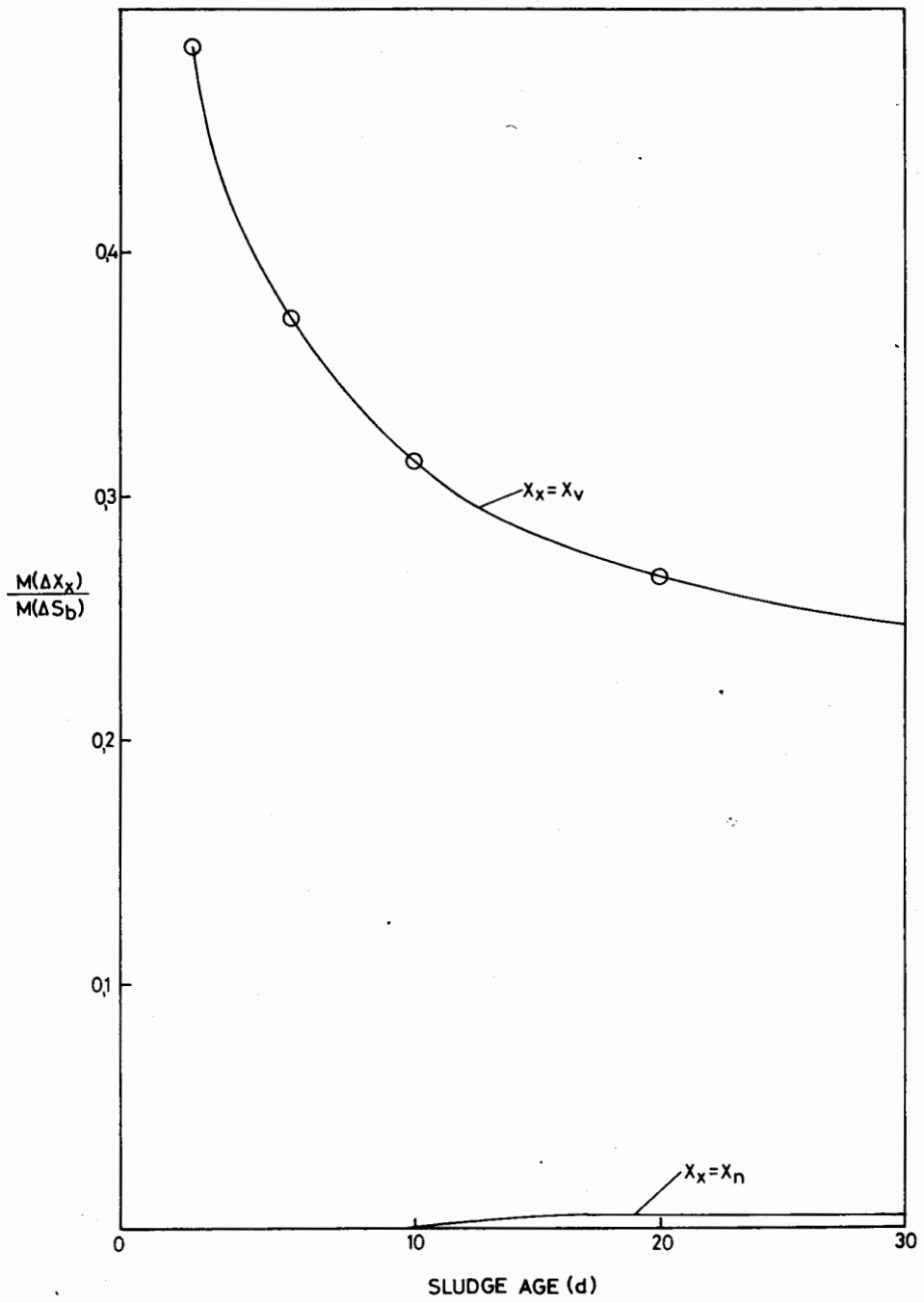


Fig.2.2: Comparison of the mass of nitrifier produced in a CMASP under constant flow and load relative to the mass of heterotrophs produced.

2.2.3(a.2) Theoretical significance of Y_n in nitrification

A theoretical evaluation of X_n is needed in order to determine the nitrification rate under changing conditions of flow and ammonia concentration. Associated with X_n is the value accorded to the maximum specific nitrification rate constant μ_{nmT}. The concentration of nitrifiers, X_n and μ_{nmT} are interrelated in the sense that $\mu_{nmT}.X_n$ defines the rate of nitrification; if for the *same* rate X_n is estimated at a high figure, μ_{nmT} must necessarily be low and *vice versa* to keep $\mu_{nmT}.X_n$ = constant.

The evaluation of X_n requires knowledge of Y_n and b_{nT}. In the absence of data to fix these two parameters accurately it is necessary, for consistency in reporting μ_{nmT} values, to standardise the values of Y_n and b_{nT}. In all the models proposed by Marais and his group the following standard values were accepted: Y_n = 0,10 (mg VSS. mg N^{-1}], b_{n20} = 0,04 [d^{-1}]. All the μ_{nmT} values reported by them are relative to these two values.

Under constant flow and load conditions it is possible to describe the behavioural pattern of nitrification without the knowledge of X_n. This is achieved by eliminating X_n as done in the derivation of Eq. (2.8), i.e. *under conditions of constant flow and load* the value of Y_n becomes immaterial.

2.2.3(b) Choice of value for K_{nT}

By accepting a set of standard average values for the nitrification constants i.e. μ_{nm20} = 0,5[d^{-1}] and b_{n20} = 0,04[d^{-1}], Fig. 2.2b compares the effect of K_{nT} on R_{sm} and on N_{ae} for $R_s > R_{sm}$. From Fig. 2.2b it is obvious that K_{nT} has hardly any effect on R_{sm}. Furthermore, for operational sludge ages of at least 1,25 times the minimum sludge age, the effluent ammonia concentration is low irrespective of the K_{nT} value. Hence knowledge of the exact value of K_{nT} is of no practical significance and an average value of K_{n20} = 1,0 [mg N.ℓ^{-1}] is accepted.

2.2.3(c) Choice of value for b_{nT}

By accepting a set of standard average values for the nitrification constants i.e. μ_{nm20} = 0,5[d^{-1}] and K_{n20} = 1,0[mg N.ℓ^{-1}],

Fig 2.2c compares the effect of b_{nT} on R_{sm} and on N_{ae} for $R_s > R_{sm}$. From Fig 2.2c it can be seen that the effect of b_{nT} on R_{sm} is of no great significance and the effect of b_{nT} on the effluent ammonia concentration for $R_s \geq 1{,}25\ R_{sm}$ is negligible. Hence knowledge of the exact value of b_{nT} is of no great importance and an average value of $b_{n20} = 0{,}04[d^{-1}]$ is accepted.

2.2.3(d) The significance of μ_{nmT} in nitrification

By accepting a set of standard average values for the nitrification constants i.e. $K_{n20} = 1{,}0[mg\ N.\ell^{-1}]$ and $b_{n20} = 0{,}04[d^{-1}]$, Fig. 2.2a compares the effect of μ_{nmT} on R_{sm} and on N_{ae}.

Fig. 2.2a clearly indicates that μ_{nmT} has a marked effect on the value of R_{sm} but at $R_s > 1{,}3\ R_{sm}$ the effect on N_{ae} is insignificant. The knowledge of R_{sm} is crucial in designing a nitrification system hence an accurate estimation of μ_{nmT} is the key to a successful prediction of nitrification behaviour in an activated sludge plant.

The value of μ_{nmT} has been observed to vary with virtually every source of sewage and to vary between different batches of the same source.

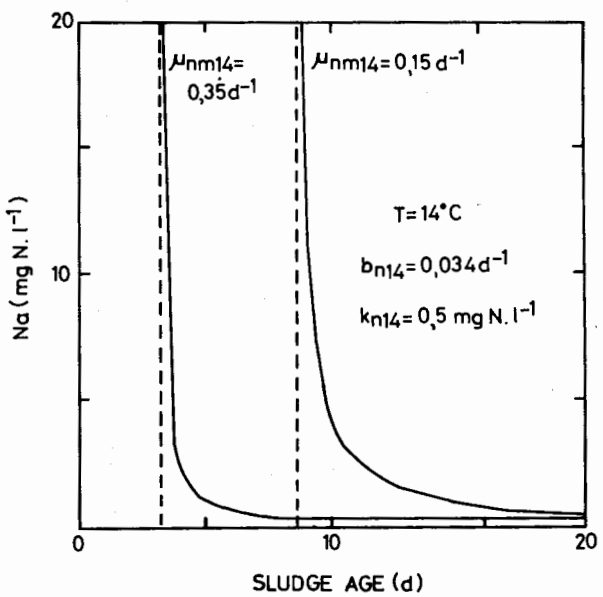


Fig.2.2a: Effect of μ_{nmT} on nitrification.

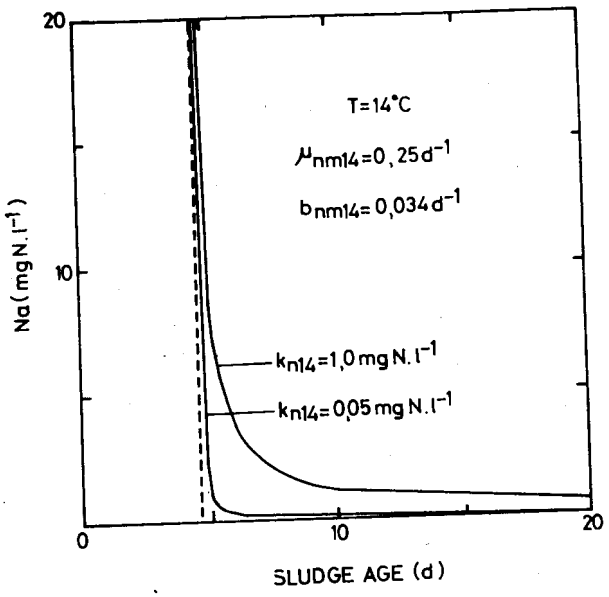


Fig.2.2b: Effect of K_{nT} on nitrification.

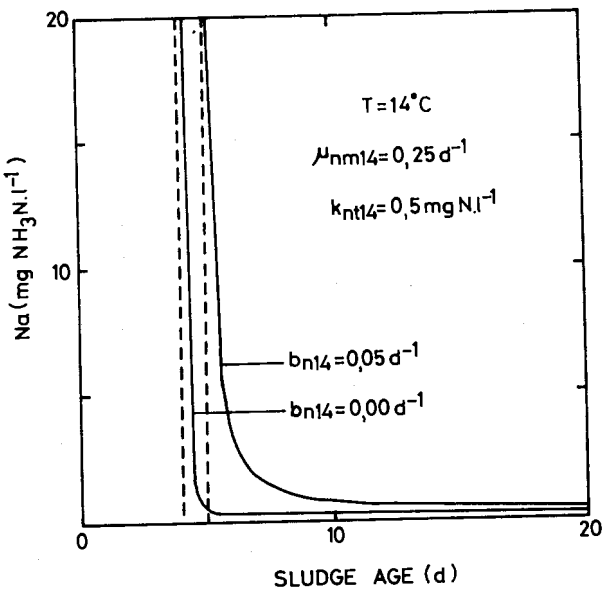


Fig.2.2c: Effect of b_{nT} on nitrification.

It therefore should be classified as a sewage characteristic rather than a kinetic constant. The reason for the marked variations in μ_{nmT} of a certain source is not completely clear. It does not appear to be a matter of toxicity but rather of inhibition and the degree of inhibition seems to be related to the fraction of industrial waste flow in the process. Due to the link between waste flow and μ_{nmT}, the value of μ_{nmT} should always be measured for the specific sewage to be dealt with.

2.2.4 Determination of μ_{nmT}

Theoretically the values of μ_{nmT}, K_{nT} and b_{nT} should be amenable to determination by calibration of Eq. (2.8) to a series of data on N_{ae} obtained over a range of sludge ages. The difficulty with this method is that in the region $R_s > R_{sm}$ the effluent ammonia is very insensitive to μ_{nmT}, b_{nT} and K_{nT} (see Figs. 2.2a, 2.2b and 2.2c). The only measurement that would be of use is to determine μ_{nmT} by operating at certain $R_s = R_{sm}$ but this is a region of instability and it requires patient and tedious experimentation to obtain reliable data.

To overcome the problems of the approach above, Ekama *et al* (1979) employed a series aerobic reactor system under cyclic loading conditions in order to create the transient conditions from which constants can be obtained by calibration. Again this approach has not been completely satisfactory. The uncertainty in this approach stems from the marked hydraulic effects of cyclic loading: slight error in the measurement of the flows results in marked variations in the respective recycles and consequently it is not possible to determine precise estimates for μ_{nmT}.

It is evident from the review above that there is a need for either improvement of the series reactor system or development of an alternative method that allows reliable determination of μ_{nmT}. These two alternatives form a substantial part of the research reported later in this thesis.

2.2.5 Incorporation of nitrification behaviour in aerobic-anoxic systems in a general model

When the general model of Dold, Ekama and Marais (1980) was adapted to aerobic-anoxic environment by Ekama *et al* (1979), the modifications concerning *nitrification* that needed to be made were:

(1) There is no nitrification in an anoxic environment, i.e. $(\mu_{nmT})_{anoxic} = 0$.

(2) Nitrifiers can grow only in an aerobic environment (obligate aerobes) but undergo death (with its associated substrate release by lysis) in both aerobic and unaerated zones.

(3) The model presupposes that an anoxic environment does not have a direct effect on the nitrification reaction kinetics of a subsequent aerobic environment - experimental evidence reported later in this work supports this hypothesis.

2.3 Denitrification

2.3.1 Stoichiometry of denitrification

Denitrification is a biologically mediated reaction known as dissimilative reduction of nitrate. It involves the reduction of nitrate or nitrite present in the wastewater to gaseous nitrogen, which escapes to the atmosphere.

The denitrification reaction is mediated by heterotrophic organisms; in the denitrification reaction these organisms obtain energy by the oxidation of organic material with nitrate and nitrite acting as electron acceptors. Usually the mass of nitrite present is negligible compared to that of nitrate (see Section 2.1.1) so that the reduction of nitrate only is of significance.

In terms of electron equivalents, the half reactions for the reduction of oxygen and nitrate can be compared:

Oxygen $$1/4[O_2] + [H^+] + \ell_q^- = 1/2\,[H_2O] \qquad (2.3.1)$$

Nitrate $$1/5[NO_3^-] + 6/5[H^+] + \ell_q^- = 1/10[N_2] + 3/5[H_2O] \qquad (2.3.2)$$

Considering Eq. (2.3.1), the transfer of one electron equivalent (ℓ_q^-) is accomplished by the reduction of 1/4 mole of oxygen, i.e. 8g.

This transfer corresponds to the oxidation of 8g COD of the organic compounds (from the definition of the COD test below*).

Considering Eq. (2.3.2), the transfer of one ℓ_q^- is accomplished by reduction of 1/5 mole of nitrate i.e. 62/5 g. If nitrate is measured in terms of the nitrogen atom i.e. in terms of (NO_3-N), then one ℓ_q^- is equivalent to the reduction of $(\frac{62}{5}).(\frac{14}{62})$ = 2,80 g (NO_3-N). Equating the electron equivalence of nitrate and oxygen from Eqs. (2.3.2 and 2.3.1) respectively, it follows that

2,80 g (NO_3-N) ≡ 8 g O
i.e.
1 mg (NO_3-N) ≡ 2,86 mg O (or mg COD).

Equation (2.3.2) is a half reaction describing the reduction of nitrate. The corresponding half reaction describing the oxidation of COD (of a general formula $C_x H_y O_z$) is

$$\frac{1}{4X+Y-2Z} C_x H_y O_z + \frac{2X-Z}{4X+Y-2Z} H_2O \rightarrow \frac{X}{4X+Y-2Z} CO_2 + H^+ + \ell_q^- \qquad (2.3.3)$$

Combining Eqs. (2.3.2 and 2.3.3), the following redox reaction can be written

$$\frac{1}{4X+Y-2Z} C_x H_y O_z + [\frac{2X-Z}{4X+Y-2Z} - \frac{3}{5}] H_2O + \frac{1}{5} [NO_3^-] + \frac{1}{5} [H^+] \rightarrow$$

$$\rightarrow \frac{X}{4X+Y-2Z} CO_2 + 1/10\ N_2 \qquad (2.3.4)$$

Hence, during denitrification of 1 mole of NO_3, 1 mole of H+ is consumed.

2.3.2(a) Oxygen recovery associated with denitrification

In Section 2.1.3 it was shown that for every 1 mg NH_4^+-N of ammonia converted to nitrate, 4,57 mg O are consumed, and in Section 2.3.1 that for every 1 mg (NO_3-N) reduced to nitrogen gas, 2,86 mg O

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*The COD test is a measure for the electron transfer potential of the organic matter [after Van Haandel and Marais (1981)].

are recovered equivalently. Thus, in the denitrification process of a single sludge system a fraction (2,86/4,57) = 0,625 of the oxygen required for nitrification can be reocvered as equivalent oxygen.

2.3.2(b) Effect of denitrification on alkalinity

The conversion of one mole of ammonia to nitrate (nitrification), produces 2 moles of H+ (Eq.2.2), i.e. the nitrification of 1 mg (NH_4^+-N) to nitrate consumes 7,14 mg alkalinity as $CaCO_3$ [Section 2.1.2]. Denitrification of one mole of nitrate to nitrogen gas consumes 1 mole of H^+ (Eq. 2.3.4). Hence for each mole of ammonia expressed as N i.e. (NH_4^+-N) (≡ 14 g) converted to nitrogen gas, there is a nett production of (2-1) = 1 mole of H^+ (i.e. 1 g H^+) or, equivalently, a nett consumption of 50 g of alkalinity expressed as $CaCO_3$ [Loewenthal and Marais (1976)], i.e. per one mg of nitrified and subsequently denitrified nitrogen there is a nett decrease of 50/14 = 3,57 mg of alkalinity expressed as $CaCO_3$.

2.3.3 Empirical approach to denitrification

Stern and Marais (1974) found that under *constant flow and load conditions* denitrification is approximately a zero order reaction with respect to nitrate concentration, and directly proportional to the active mass concentration. Hence under constant flow and load conditions the rate of denitrification could be described by an equation of the type

$$\Delta N/\Delta t = -K.X_a$$

Experimentally three rates were identified: in a predenitrification reactor, receiving the influent, two rates were apparent (specified by K_{1T}- and K_{2T}- rate constants) and in a post-denitrification reactor a single rate, K_{3T}- rate constant.

The rate constant K_{1T} was high, giving rise to a rapid rate of denitrification, but it terminated after a few minutes; the total removal of nitrogen associated with K_{1T} was observed to be proportional to the influent COD. The rate associated with K_{2T} continued for the balance of the time in the reactor, at about 1/7 the first rate.

The rate associated with K_{3T} was lower than that associated with K_{2T} (i.e. the value of K_{3T} was lower than that for K_{2T}) and continued for the total period of time in the post-denitrification reactor. The rates were temperature dependent but apparently independent of the sludge age for sludge ages between 10 and 22 days.

The retention time in the pre-denitrification reactor normally is long enough to allow completion of the rate associated with K_{1T}. Consequently it was possible to write the denitrification of a process having both pre- and post-anoxic reactors *under constant flow and load conditions* as follows:

$$\Delta N=\Delta N_1+\Delta N_2+\Delta N_3 = \alpha.S_{ti}+K_{2T}.(R_1-R_0).X_a+K_{3T}R_3X_a \qquad (2.3.5)$$

where

ΔN = Total nitrogen removal [mg NO_3-N.ℓ^{-1}]

α = Predenitrification mass concentration constant during which K_{1T} is operative [mg NO_3-N.mg COD^{-1}]

R_0 = Nominal retention time during which K_{1T} is operative [d]

R_1 = Total nominal retention time in the predenitrification reactor [d]

R_3 = Nominal retention time in the post-denitrification reactor [d]

S_{ti} = Total influent COD concentration [mg COD.ℓ^{-1}]

Note that the denitrification formulation expressed in Eq. (2.3.5) is applicable only under constant flow and load conditions, and is empirical, based on observed behaviour.

2.3.4 Application of the bi-substrate theory to denitrification

In 1978 (published in 1980) Dold, Ekama and Marais proposed that the biodegradable material in municipal waste flow is composed of an easily biodegradable fraction, f_{ca}, which is of a soluble nature (and is utilized at a high rate by the micro-organisms) and a slowly biodegradable fraction, $(1-f_{ca})$, which is of a particulate nature (and is utilized at a relatively low rate). Ekama, Van Haandel and Marais (1979) suggested that K_{1T} is associated with the utilization

2.2.3(a.2) Theoretical significance of Y_n in nitrification

A theoretical evaluation of X_n is needed in order to determine the nitrification rate under changing conditions of flow and ammonia concentration. Associated with X_n is the value accorded to the maximum specific nitrification rate constant μ_{nmT}. The concentration of nitrifiers, X_n and μ_{nmT} are interrelated in the sense that $\mu_{nmT}.X_n$ defines the rate of nitrification; if for the *same* rate X_n is estimated at a high figure, μ_{nmT} must necessarily be low and *vice versa* to keep $\mu_{nmT}.X_n$ = constant.

The evaluation of X_n requires knowledge of Y_n and b_{nT}. In the absence of data to fix these two parameters accurately it is necessary, for consistency in reporting μ_{nmT} values, to standardise the values of Y_n and b_{nT}. In all the models proposed by Marais and his group the following standard values were accepted: Y_n = 0,10 (mg VSS. mg N^{-1}], b_{n20} = 0,04 [d^{-1}]. All the μ_{nmT} values reported by them are relative to these two values.

Under constant flow and load conditions it is possible to describe the behavioural pattern of nitrification without the knowledge of X_n. This is achieved by eliminating X_n as done in the derivation of Eq. (2.8), i.e. *under conditions of constant flow and load* the value of Y_n becomes immaterial.

2.2.3(b) Choice of value for K_{nT}

By accepting a set of standard average values for the nitrification constants i.e. μ_{nm20} = 0,5[d^{-1}] and b_{n20} = 0,04[d^{-1}], Fig. 2.2b compares the effect of K_{nT} on R_{sm} and on N_{ae} for $R_s > R_{sm}$. From Fig. 2.2b it is obvious that K_{nT} has hardly any effect on R_{sm}. Furthermore, for operational sludge ages of at least 1,25 times the minimum sludge age, the effluent ammonia concentration is low irrespective of the K_{nT} value. Hence knowledge of the exact value of K_{nT} is of no practical significance and an average value of K_{n20} = 1,0 [mg $N.\ell^{-1}$] is accepted.

2.2.3(c) Choice of value for b_{nT}

By accepting a set of standard average values for the nitrification constants i.e. μ_{nm20} = 0,5[d^{-1}] and K_{n20} = 1,0[mg $N.\ell^{-1}$],

Fig 2.2c compares the effect of b_{nT} on R_{sm} and on N_{ae} for $R_s > R_{sm}$. From Fig 2.2c it can be seen that the effect of b_{nT} on R_{sm} is of no great significance and the effect of b_{nT} on the effluent ammonia concentration for $R_s \geq 1{,}25\ R_{sm}$ is negligible. Hence knowledge of the exact value of b_{nT} is of no great importance and an average value of $b_{n20} = 0{,}04[d^{-1}]$ is accepted.

2.2.3(d) The significance of μ_{nmT} in nitrification

By accepting a set of standard average values for the nitrification constants i.e. $K_{n20} = 1{,}0[\text{mg N.}\ell^{-1}]$ and $b_{n20} = 0{,}04[d^{-1}]$, Fig. 2.2a compares the effect of μ_{nmT} on R_{sm} and on N_{ae}.

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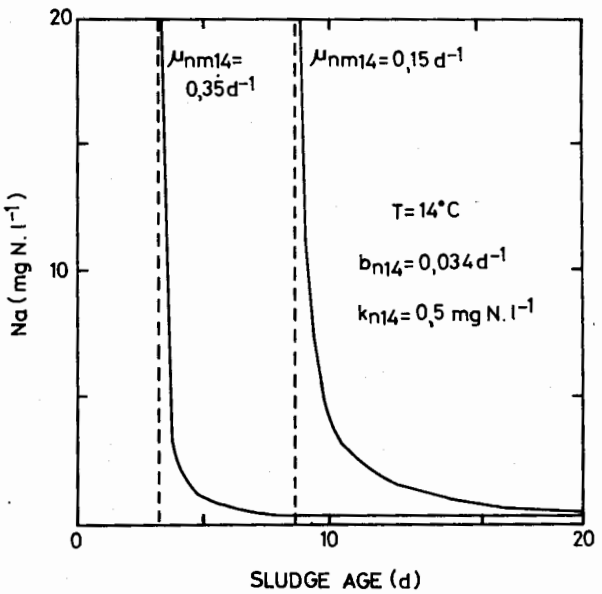

Fig.2.2a: Effect of μ_{nmT} on nitrification.

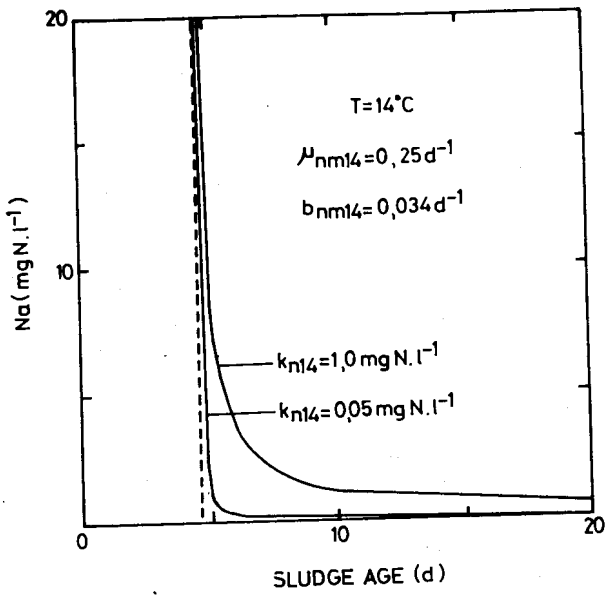

Fig.2.2b: Effect of K_{nT} on nitrification.

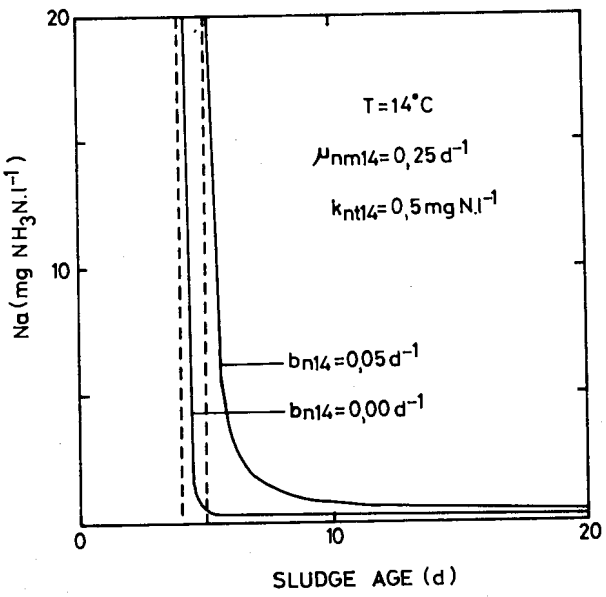

Fig.2.2c: Effect of b_{nT} .on nitrification.

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When the general model of Dold, Ekama and Marais (1980) was adapted to aerobic-anoxic environment by Ekama *et al* (1979), the modifications concerning *nitrification* that needed to be made were:

(1) There is no nitrification in an anoxic environment, i.e. $(\mu_{nmT})_{anoxic} = 0$.

(2) Nitrifiers can grow only in an aerobic environment (obligate aerobes) but undergo death (with its associated substrate release by lysis) in both aerobic and unaerated zones.

(3) The model presupposes that an anoxic environment does not have a direct effect on the nitrification reaction kinetics of a subsequent aerobic environment - experimental evidence reported later in this work supports this hypothesis.

2.3 Denitrification

2.3.1 Stoichiometry of denitrification

Denitrification is a biologically mediated reaction known as dissimilative reduction of nitrate. It involves the reduction of nitrate or nitrite present in the wastewater to gaseous nitrogen, which escapes to the atmosphere.

The denitrification reaction is mediated by heterotrophic organisms; in the denitrification reaction these organisms obtain energy by the oxidation of organic material with nitrate and nitrite acting as electron acceptors. Usually the mass of nitrite present is negligible compared to that of nitrate (see Section 2.1.1) so that the reduction of nitrate only is of significance.

In terms of electron equivalents, the half reactions for the reduction of oxygen and nitrate can be compared:

Oxygen $$1/4[O_2] + [H^+] + \ell_q^- = 1/2\,[H_2O] \quad . \qquad (2.3.1)$$

Nitrate $$1/5[NO_3^-] + 6/5[H^+] + \ell_q^- = 1/10[N_2] + 3/5[H_2O] \qquad (2.3.2)$$

Considering Eq. (2.3.1), the transfer of one electron equivalent (ℓ_q^-) is accomplished by the reduction of 1/4 mole of oxygen, i.e. 8g.

This transfer corresponds to the oxidation of 8g COD of the organic compounds (from the definition of the COD test below*).

Considering Eq. (2.3.2), the transfer of one ℓ_q^- is accomplished by reduction of 1/5 mole of nitrate i.e. 62/5 g. If nitrate is measured in terms of the nitrogen atom i.e. in terms of $(NO_3\text{-}N)$, then one ℓ_q^- is equivalent to the reduction of $(\frac{62}{5}).(\frac{14}{62})$ = 2,80 g $(NO_3\text{-}N)$. Equating the electron equivalence of nitrate and oxygen from Eqs. (2.3.2 and 2.3.1) respectively, it follows that

2,80 g $(NO_3\text{-}N) \equiv$ 8 g O
i.e.
1 mg $(NO_3\text{-}N) \equiv$ 2,86 mg O (or mg COD).

Equation (2.3.2) is a half reaction describing the reduction of nitrate. The corresponding half reaction describing the oxidation of COD (of a general formula $C_x H_y O_z$) is

$$\frac{1}{4X+Y-2Z} C_x H_y O_z + \frac{2X-Z}{4X+Y-2Z} H_2O \rightarrow \frac{X}{4X+Y-2Z} CO_2 + H^+ + \ell_q^- \qquad (2.3.3)$$

Combining Eqs. (2.3.2 and 2.3.3), the following redox reaction can be written

$$\frac{1}{4X+Y-2Z} C_x H_y O_z + [\frac{2X-Z}{4X+Y-2Z} - \frac{3}{5}] H_2O + \frac{1}{5} [NO_3^-] + \frac{1}{5} [H^+] \rightarrow$$

$$\rightarrow \frac{X}{4X+Y-2Z} CO_2 + 1/10\ N_2 \qquad (2.3.4)$$

Hence, during denitrification of 1 mole of NO_3, 1 mole of H+ is consumed.

2.3.2(a) Oxygen recovery associated with denitrification

In Section 2.1.3 it was shown that for every 1 mg NH_4^+-N of ammonia converted to nitrate, 4,57 mg O are consumed, and in Section 2.3.1 that for every 1 mg $(NO_3\text{-}N)$ reduced to nitrogen gas, 2,86 mg O

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*The COD test is a measure for the electron transfer potential of the organic matter [after Van Haandel and Marais (1981)].

are recovered equivalently. Thus, in the denitrification process of a single sludge system a fraction (2,86/4,57) = 0,625 of the oxygen required for nitrification can be reocvered as equivalent oxygen.

2.3.2(b) Effect of denitrification on alkalinity

The conversion of one mole of ammonia to nitrate (nitrification), produces 2 moles of H+ (Eq.2.2), i.e. the nitrification of 1 mg (NH_4^+-N) to nitrate consumes 7,14 mg alkalinity as $CaCO_3$ [Section 2.1.2]. Denitrification of one mole of nitrate to nitrogen gas consumes 1 mole of H^+ (Eq. 2.3.4). Hence for each mole of ammonia expressed as N i.e. (NH_4^+-N) ($\equiv$ 14 g) converted to nitrogen gas, there is a nett production of (2-1) = 1 mole of H^+ (i.e. 1 g H^+) or, equivalently, a nett consumption of 50 g of alkalinity expressed as $CaCO_3$ [Loewenthal and Marais (1976)], i.e. per one mg of nitrified and subsequently denitrified nitrogen there is a nett decrease of 50/14 = 3,57 mg of alkalinity expressed as $CaCO_3$.

2.3.3 Empirical approach to denitrification

Stern and Marais (1974) found that under *constant flow and load conditions* denitrification is approximately a zero order reaction with respect to nitrate concentration, and directly proportional to the active mass concentration. Hence under constant flow and load conditions the rate of denitrification could be described by an equation of the type

$$\Delta N/\Delta t = -K.X_a$$

Experimentally three rates were identified: in a predenitrification reactor, receiving the influent, two rates were apparent (specified by K_{1T}- and K_{2T}- rate constants) and in a post-denitrification reactor a single rate, K_{3T}- rate constant.

The rate constant K_{1T} was high, giving rise to a rapid rate of denitrification, but it terminated after a few minutes; the total removal of nitrogen associated with K_{1T} was observed to be proportional to the influent COD. The rate associated with K_{2T} continued for the balance of the time in the reactor, at about 1/7 the first rate.

The rate associated with K_{3T} was lower than that associated with K_{2T} (i.e. the value of K_{3T} was lower than that for K_{2T}) and continued for the total period of time in the post-denitrification reactor. The rates were temperature *dependent but apparently* independent of the sludge age for sludge ages between 10 and 22 days.

The retention time in the pre-denitrification reactor normally is long enough to allow completion of the rate associated with K_{1T}. Consequently it was possible to write the denitrification of a process having both pre- and post-anoxic reactors *under constant flow and load conditions* as follows:

$$\Delta N=\Delta N_1+\Delta N_2+\Delta N_3 = \alpha.S_{ti}+K_{2T}.(R_1-R_0).X_a+K_{3T}R_3X_a \qquad (2.3.5)$$

where

ΔN = Total nitrogen removal [mg NO_3-N.ℓ^{-1}]

α = Predenitrification mass concentration constant during which K_{1T} is operative [mg NO_3-N.mg COD^{-1}]

R_0 = Nominal retention time during which K_{1T} is operative [d]

R_1 = Total nominal retention time in the predenitrification reactor [d]

R_3 = Nominal retention time in the post-denitrification reactor [d]

S_{ti} = Total influent COD concentration [mg COD.ℓ^{-1}]

Note that the denitrification formulation expressed in Eq. (2.3.5) is applicable only under constant flow and load conditions, and is empirical, based on observed behaviour.

2.3.4 Application of the bi-substrate theory to denitrification

In 1978 (published in 1980) Dold, Ekama and Marais proposed that the biodegradable material in municipal waste flow is composed of an easily biodegradable fraction, f_{ca}, which is of a soluble nature (and is utilized at a high rate by the micro-organisms) and a slowly biodegradable fraction, $(1-f_{ca})$, which is of a particulate nature (and is utilized at a relatively low rate). Ekama, Van Haandel and Marais (1979) suggested that K_{1T} is associated with the utilization

of easily biodegradable substrate while K_{2T} is associated with the utilization of slowly biodegradable substrate. Hypothesizing that the reactions associated with K_{1T} and K_{2T} take place independently and simultaneously instead of sequentially as assumed by Stern and Marais (1974), Ekama *et al* (1979) recalculated K_{1T}, K_{2T} and K_{3T} as

$K_{1T} = 0,72 \ (1,2)^{T-20}$ [mg N. mg $X_a^{-1}.d^{-1}$]

$K_{2T} = 0,101 \ (1,08)^{T-20}$ [- " -]

$K_{3T} = 0,079 \ (1,03)^{T-20}$ [- " -]

Utilizing the redefinition of K_{1T} and K_{2T} as proposed by Ekama *et al* (1979), Eq. (2.3.5) may be rewritten as

$$\Delta N=\Delta N_1+\Delta N_2+\Delta N_3 = \alpha S_{ti}+K_{2T}R_1.X_a+K_{3T}R_3X_a \qquad (2.3.6)$$

It was noted in Section 2.2.2 that, for practical reasons, the value of the maximum anoxic sludge mass fraction, f_{xm}, must not exceed $f_{xm} = 0,50$. This restriction sets an upper limit to denitrification associated with the utilization of the slowly biodegradable substrate:

For a single sludge system, having a pre-denitrification reactor only, the empirical description of denitrification (Eq. 2.3.6) reduces to

$$\Delta N=\Delta N_1+\Delta N_2 = \alpha.S_{ti}+K_{2T}R_1.X_a \qquad (2.3.6a)$$

Equation (2.3.6a) indicates that the nitrogen removal associated with the utilization of slowly biodegradable substrate in the pre-denitrification reactor, ΔN_2, is directly proportional to the nominal hydraulic retention time of the predenitrification reactor, R_1. i.e.

$$\Delta N_2 = K_{2T}.R_1.X_a = K_{2T}.(R_1/R_h).X_a.R_h$$

where

R_h = Total hydraulic retention time of the process [d].

Now,

$$\frac{R_1}{R_h} = \frac{V_1}{V_T} = \frac{V_1 X_a}{V_T X_a} = \frac{M(X_a)_1}{M(X_a)} = f_{x1}$$

i.e.

$$\Delta N_2 = K_{2T} \cdot f_{x1} \cdot R_h \cdot X_a$$

where

V_1 = Volume of predenitrification reactor [ℓ]

V_T = Total volume of the process [ℓ]

X_a = Active sludge *mass concentration* throughout the process [mg VSS.ℓ^{-1}]

$M(X_a)_1$ = Active sludge *mass* in the predenitrification reactor [mg VSS]

$M(X_a)$ = Total active sludge mass in the process [mg VSS]

f_{x1} = Sludge mass fraction in the predenitrification reactor [mg VSS.mg VSS^{-1}]

For a predenitrification system

$f_{x1} \leq f_{xm}$

The magnitude of f_{x1} governs the nitrogen removal associated with the utilization of slowly biodegradable substrate in a predenitrification reactor and is subject to an upper limit, $f_{x1} \leq 0{,}50$.

Returning to Eq. (2.3.6), this equation constitutes an empirical description of the denitrification behaviour under constant flow and load conditions; essentially the formulation is unrelated to any biological kinetic behaviour.

In order to explain *kinetically* the observed denitrification behaviour under constant flow and load conditions, it was necessary to obtain a general model of activated sludge *kinetics* that describes the denitrification behaviour under constant, cyclic and any other general pattern of flow and load.

2.3.5 Incorporation of denitrification behaviour in the general model

The general activated sludge theory including denitrification is an extension of the general aerobic theory. In order to appreciate the significance of this extension it is useful to examine the development of the general aerobic theory.

Marais and Ekama (1976) developed an aerobic model based on that of Lawrence and McCarty (1970). The latters' model accepted that

(1) the Monod equation relates the specific organism growth rate to the concentration of soluble substrate surrounding the organism, and

(2) concomitant with growth, there is a continuous loss of active mass (endogenous respiration). Furthermore, Lawrence and McCarty established the link between sludge age and food/microorganism ratio.

Marais and Ekama (1976) extended the Lawrence and McCarty model by including (1) the generation of endogenous residue due to endogenous respiration as first proposed by McKinney and Symons (1964), and (2) the accumulation of inert volatile solids due to the presence of this material in the influent (McKinney 1966). Furthermore, (3) they established the relationship between oxygen utilization and the synthesis and endogenous respiration reactions, respectively.

Important aspects arising from the model proposed by Marais and Ekama (1976) are:

(1) A distinction is made between the active and inert sludge fractions.

(2) The biological reactions are expressed in terms of *active* mass.

(3) The oxygen uptake rate is determined directly from the biological reactions.

Application of this model to a single reactor with domestic wastewater as influent under *constant* flow and load conditions was in

good agreement with observed results. Application of the model to completely mixed activated sludge (CMAS) process under cyclic flow conditions, using a glucose feed to the system, also showed close correlation between predicted and observed values (Dold, Ekama and Marais 1980) [see Fig. 2.3]. However, when the model was applied to cyclically loaded CMAS processes receiving domestic wastewater as influent and operating at low sludge ages (R_s = 2,5 days), it was found impossible to correlate the predicted and observed oxygen consumption rates. At the instant of feed termination there was a precipitous drop in oxygen consumption rate and thereafter a continuous high rate of oxygen consumption for a period of about 2 hours followed by a slow decrease to the oxygen uptake rate associated with endogenous respiration, (see Fig. 2.4). This behaviour could not be accounted for by the Marais-Ekama (1976) model, Fig. 2.4. Despite this inadequacy, the important consequence of the Marais and Ekama model was the recognition of the oxygen utilization rate as a most sensitive parameter against which the activated sludge theory can be tested.

In 1977 Ekama and Marais, based on the work of Andrews and Busby (1973), concluded that the influent COD of domestic waters is *not* soluble but totally of a particulate nature and requires adsorption and storage on the organism, and extracellular enzymatic breakdown before it can be absorbed and metabolized by the organism. They extended Andrews' model for the degradation of particulate material and presented an improved empirical kinetic relationship to determine the rate of utilization of the particulate material. This model described the behaviour of the process under cyclic flow conditions much more realistically than the previous model based on Monod's equation for the soluble COD substrate utilization rate. However, it did not explain the precipitous drop in oxygen utilization rate under a square wave feed pattern at the termination of the feed cycle (see Fig. 2.5a). Ekama and Marais (1978) initially subscribed the drop in oxygen consumption rate to a behavioural characteristic of *autotrophic* nitrification. The acceptance of this hypothesis led to the development of a *modified* model for nitrification that assumed *inter alia* that the conversion of ammonia to nitrate is instantaneous i.e. the model excluded the Monod relationship for nitrification. In

terms of their model it was necessary to accept that only 20 per cent of the TKN was in the ammonia and 80 per cent in the organic nitrogen form. Although the reverse is indicated by chemical measurement, Ekama and Marais justified their choice of the influent nitrogen fractions by hypothesizing that in the ammonia test, in fact some of the proteinaceous material is broken down to ammonia.

The nitrification model also accepted that the nitrogen required for heterotrophic growth is obtained from the organic nitrogen form rather than the ammonia form; the excess organic nitrogen is slowly converted to free and saline ammonia by the heterotrophs' action. Incorporation of these modifications into the general model gave the response shown in Fig 2.5b for 2,5 days sludge age. The precipitous decrease in the total oxygen consumption rate was now adequately predicted. Although the model was apparently successful, the exclusion of the Monod relationship for nitrification in favour of a different nitrification theory, was difficult to justify unless very powerful supporting evidence is presented.

Work by Wilson and Marais (1976) led to a reassessment of the model. Ekama and Marais (1978) hypothesized that the precipitous drop in oxygen consumption rate at feed termination may be attributed to cessation of a *heterotrophic* energy requirement for adsorption of the carbonaceous particulate substrate, caused by feed termination. (The feed was still regarded as being *all* of a particulate nature). They included this energy (oxygen) requirement for adsorption in the mathematical model and reinstated Monod relationship for nitrification, and accepted the experimentally measured nitrogen influent fractions (i.e. approximately *80% free and saline ammonia* and *20% organic nitrogen*). However they retained the concept of organic nitrogen storage associated with stored COD and the slow conversion of organic nitrogen to free and saline ammonia by the heterotrophs. A comparison of the response of this modified model with the experimental response at 2,5 days sludge age is shown by Fig. 2.6. The modified model showed a significantly improved correlation between the experimental and simulated oxygen consumption rates and nitrate concentrations. Indeed, generally, the Ekama and Marais (1978) model describes the behaviour of an aerobic CMAS process very adequately.

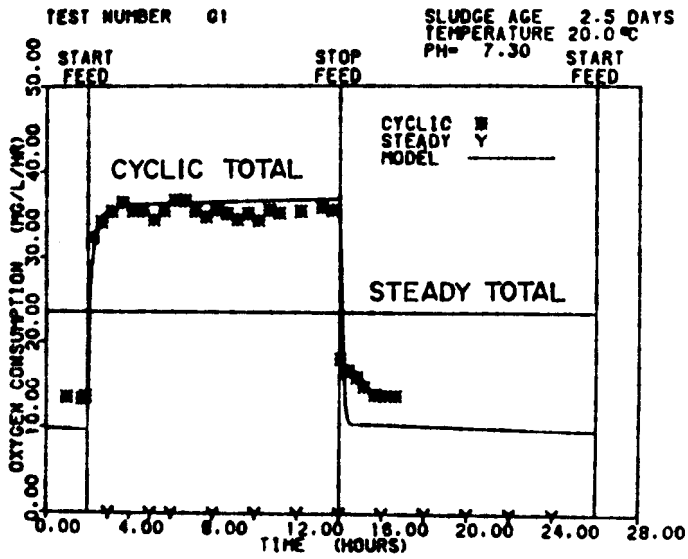

Fig.2.3: Comparison of simulated and observed response of a CMASP under cyclic flow and load with a glucose feed to the system using the Ekama & Marais(1976) model.

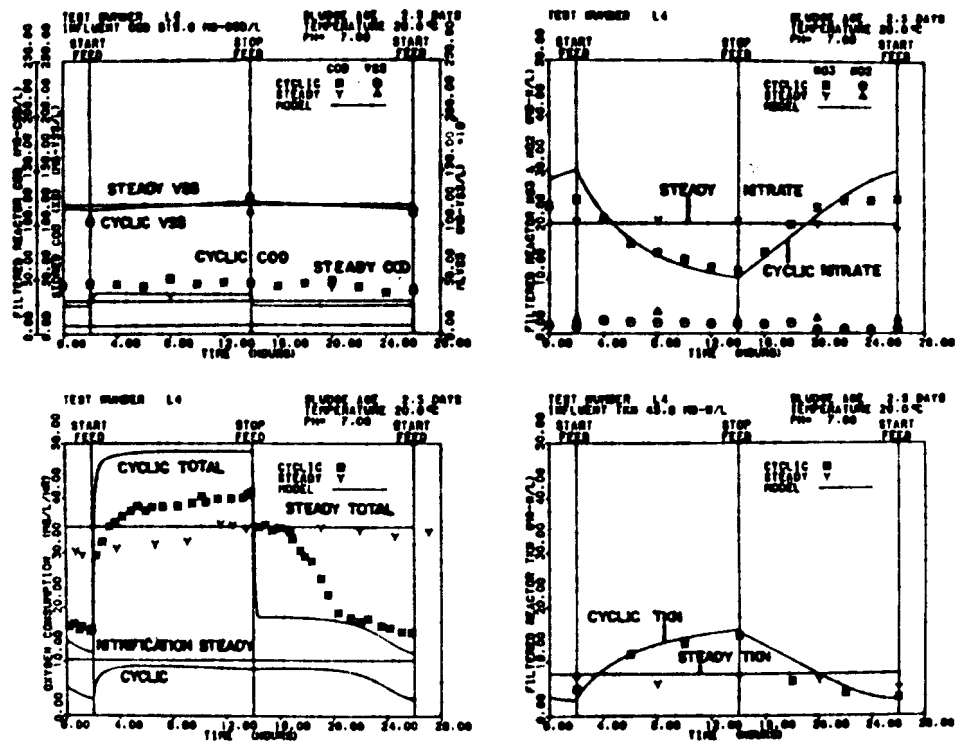

Fig.2.4: Comparison of simulated and observed response of a CMASP under cyclic flow and load with domestic sewage feed using the Ekama & Marais(1976) model.

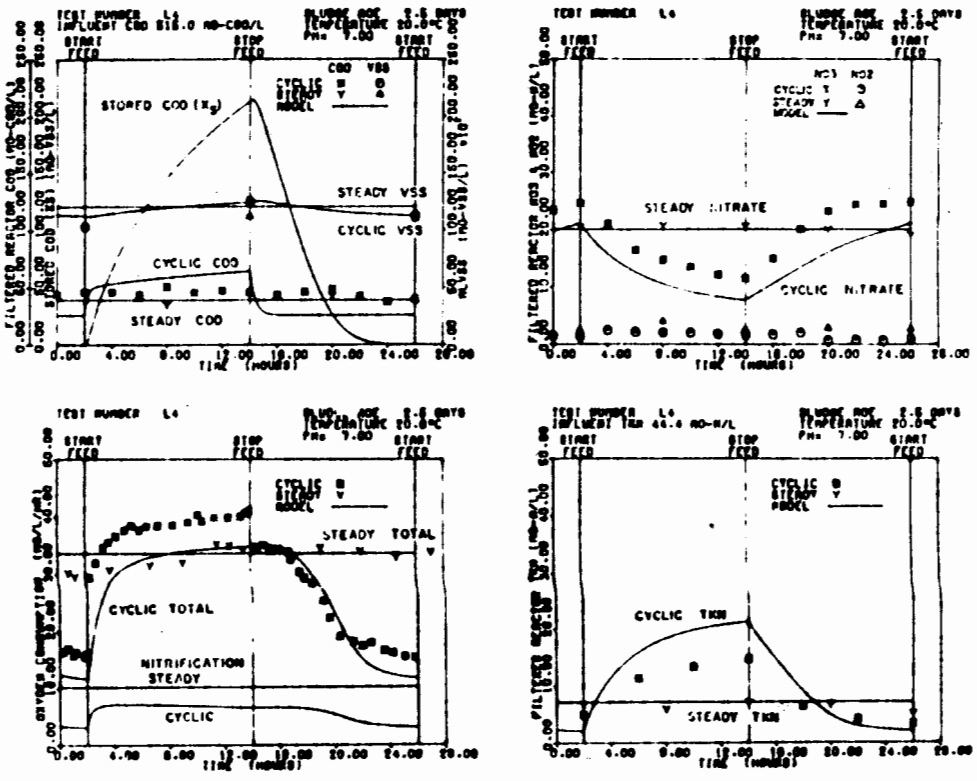

Fig.2.5a: Comparison of simulated and observed response of a CMASP under cyclic flow and load with sewage feed assuming the influent to be totally of a particulate nature [After Ekama & Marais(1977)].

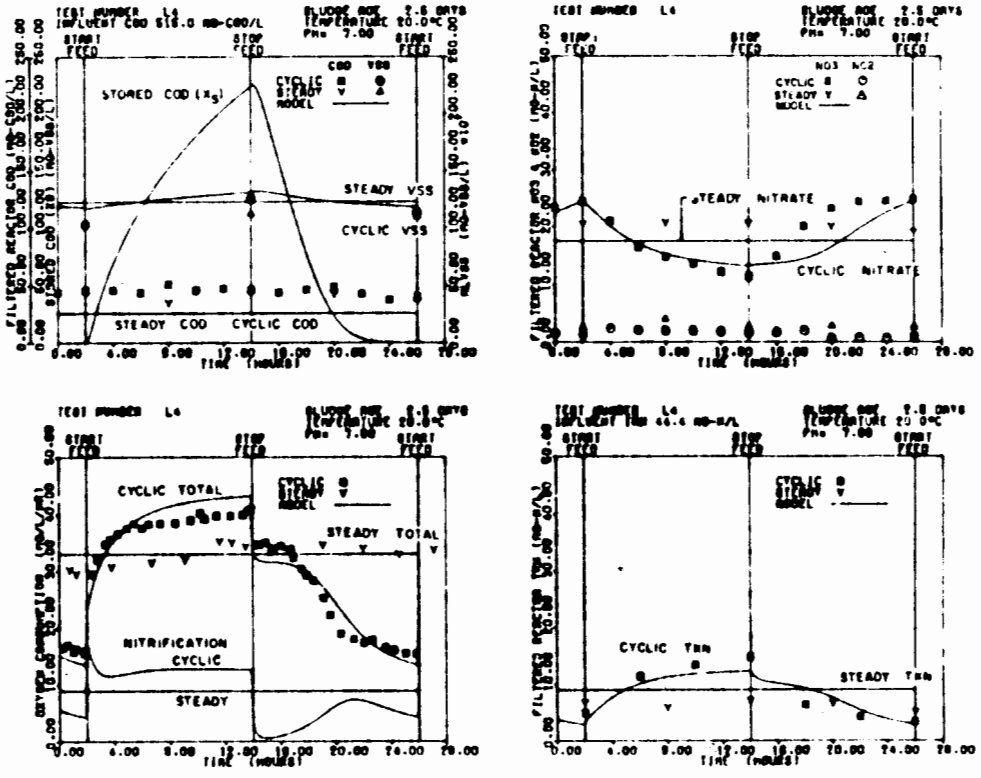

Fig.2.5b: Comparison of simulated and observed response of a CMASP under cyclic flow and load with sewage feed utilizing the Ekama & Marais(1977) model and incorporating a modified nitrification model.

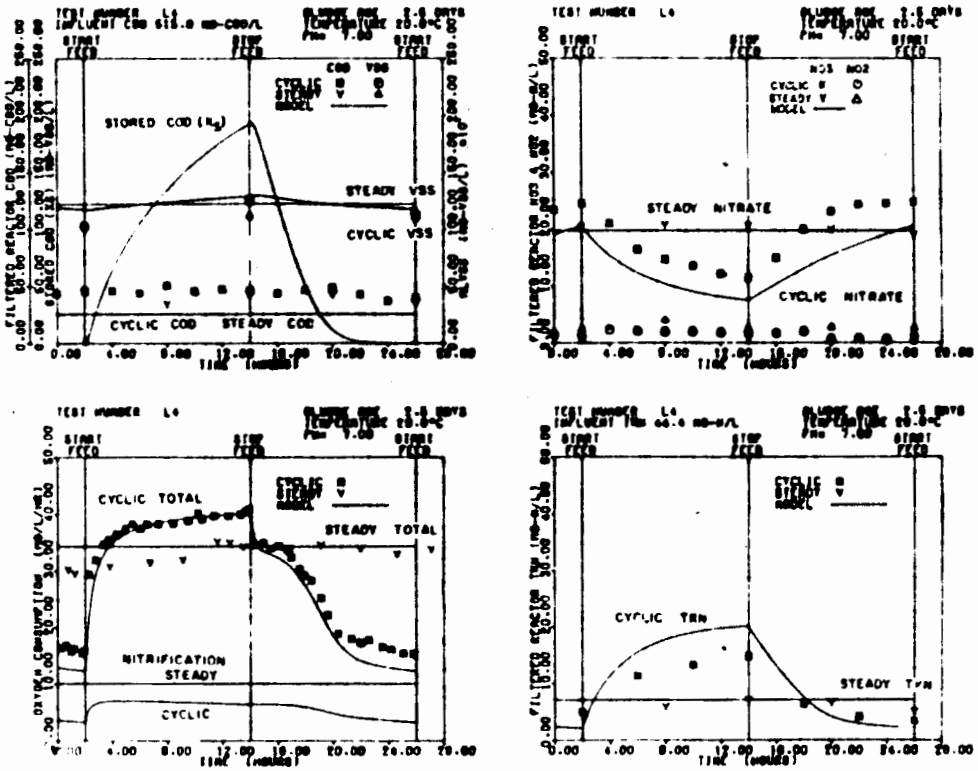

Fig.2.6: Comparison of simulated and observed response of a CMASP under cyclic flow and load with sewage feed assuming the influent to be totally of a particulate nature and incorporating the adsorption phenomena [After Ekama & Marais(1978)].

In 1979 (published in 1980) Dold, Ekama and Marais critically reviewed the model of Ekama and Marais and concluded that certain hypotheses in the Ekama and Marais model needed replacement and proposed the following:

(1) The biodegradable substrate consists of two fractions easily biodegradable soluble and slowly biodegradable particulate. The rate of utilization of the easily biodegradable material is governed by the Monod equation (Eq. 2.3.11) while that of the slowly biodegradable material is governed by a Levenspiel (1972) type equation for surface active reactions (Eq. 2.3.13).

(2) The Monod and Levenspiel reactions take place independently and simultaneously. Dold *et al* justified this assumption by hypothesizing that as the organisms essentially remain in a continuous state of stress due to the low food/microorganism ratio found in most types of activated sludge processes, it is unlikely that, in the range of operational sludge ages, the particulate material (stored on the active sites) will occupy any but a small fraction of the active sites. The only process where the particulate material may occupy a substantial fraction of the maximum fraction of substrate that can be stored on the active sites, (f_{ma}), is in the contact chamber of a contact stabilization process and, in aerated lagoons with short hydraulic retention time 1 - 2 days.*

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*Justification for the independence of the two reactions is to be found in analysing the ratio of stored material to active mass by means of the general theory of Dold, Ekama and Marais. A measure of the fraction of *unoccupied* active sites is given by $[f_{ma}-(X_s/X_a)]$. In Fig. 2.9 a plot is shown of $[f_{ma}-(X_s/X_a)]$ vs. sludge age. It is apparent that the activated sludge process is characterized by a minimum sludge age for particulate organic substrate utilization (similar to that for nitrification) below which all the active sites are occupied and the reaction achieves a stationary upper limit of utilization per unit mass of X_a.

Above about 2 days sludge age the percentage of sites available remains relatively constant in the range 90-100 per cent so that the response to soluble waste will be virtually as if no particulate material is present, i.e. the reactions of easily biodegradable and particulate biodegradable substrate, respectively, are virtually independent of each other. The interdependence of the easily biodegradable and particulate substrate, respectively, would develop in the range below about R_s = 2 days; within this range the rate of substrate utilization is uncertain.

(3) The energy requirement for adsorption can be relinquished, the precipitous drop in oxygen utilization rate at cyclic feed termination being due to termination of the easily biodegradable COD.

The modified (1979) aerobic model gave predictions very close to the observed data. However at a later stage during denitrification studies with Van Haandel, the model above showed certain inconsistencies in that the observed oxygen utilization of an aerobic reactor receiving mixed liquor from an unaerated reactor was higher than that obtained by the model prediction. All the models up to this stage assumed the synthesis-endogenous respiration approach. Basically this approach assumes that the organism is generated and subsequently undergoes mass loss due to a cell maintenance energy requirement. If this is so indeed, then a mixed liquor sample placed under batch conditions without feed addition should show an "ageing" effect. However Marais and Ekama found that the ratios of oxygen utilization rates between any two consecutive days remain constant, i.e. no ageing effect is observed.

In order to explain the behaviour characteristics described above, they hypothesized a different model for the behaviour of the organisms, i.e. the death-regeneration model. In the death-regeneration model it is hypothesized that the percentage of live mass that disappears per unit time in fact dies, lyse biodegradable substrate back into the liquid, and leaves the balance as unbiodegradable endogenous residue. The lysed biodegradable substrate is added to the biodegradable COD in the liquid and passes through the same phases of adsorption, storage and utilization. This approach, in effect, implies that endogenous respiration (cell maintenance) *per se* does not exist and that oxygen is consumed only for synthesis of new cell material from the lysed energy. In terms of this model, the average life expectation is about 1,1 days, i.e. 62 per cent of the organisms die each day and 38 per cent is regenerated giving rise to a nett decrease of 24 per cent per day. Once the sludge age exceeds about 1-2 days, the regeneration effect virtually keeps the mass at an actual organism life expectancy of 1,1 days, i.e. no ageing effect

would become apparent. Also the observations made by Ekama *et al* (1979) that high oxygen uptake rate is observed in an aerobic reactor that follows an anaerobic reactor, can be now explained: under anaerobic conditions synthesis ceases, but organism death, with associated lysis of biodegradable material continues, resulting in a build up of biodegradable material in the reactor. When effluent from the anaerobic reactor passes into an aerobic reactor, in which oxygen is available, the aerobic biodegradation of the accumulation of biodegradable substrate causes a high oxygen utilization.

The simulated response of a cyclically loaded *aerobic* CMAS process obtained by using the bi-substrate active-site death-regeneration model, when compared with observed response, gives excellent correlation not only at 2,5 days sludge age but also for a variety of process configurations under a number of influent flow and load patterns. Figure 2.7 is one simulation of a square wave, cyclically loaded 2,5 days sludge age aerobic process.

Ekama, Van Haandel and Marais (1979) extended the death-regeneration aerobic general model to include denitrification. This required making the following adjustments:

(1) Growth of nitrifiers can take place only under aerobic conditions; death is assumed to take place irrespective of aerobic or anoxic conditions.

(2) It is assumed that an anoxic environment does not have a direct effect on the nitrification reaction kinetics of a subsequent aerobic environment.

(3) Growth of heterotrophs is assumed to take place in both aerobic and anoxic conditions (i.e. provided nitrate or dissolved oxygen is available); death and lyses take place irrespective of whether the conditions are aerobic or anoxic.

Calibration of the modified general model by Van Haandel and Marais (1981), using data on pre- and post-denitrification reactors generated in a plug flow regime under constant flow and load conditions indicated that:

(1) For close fits between simulated and observed data in the post-denitrification reactor, the lysed material should be of a particulate nature.

(2) In an anoxic reactor, the utilization rate of the particulate matter takes place at a slower rate than that in an aerobic reactor [see Eq. 2.3.18)].

To indicate the adaptations that needed to be made in order to extend the aerobic model to include denitrification, the differential equations for the general aerobic model describing heterotrophic reactions are set out below:

Let

$$A = K_{msT}.S_{bs}/(S_{bs} + K_{ss}) \qquad (2.3.7)^*$$

$$B = K_{vT}.S_{bp}.(f_{ma} - X_s/X_a) \qquad (2.3.8)^*$$

$$C = K_{mpT}.P.X_s/(X_sP + K_{spT}X_a) \qquad (2.3.9)^*$$

$$D = P.b'_{hT} \qquad (2.3.10)^*$$

Then the differential equations for energy removal are:

$$dS_{bs}/dt = -A.X_a \qquad (2.3.11)^*$$

$$dS_{bp}/dt = [-B + (1-f')D].X_a \qquad (2.3.12)^*$$

$$dX_s/dt = [(B-C)/P].X_a \qquad (2.3.13)^*$$

$$dX_a/dt = [Y_h(A + C) - D/P].X_a \qquad (2.3.14)^*$$

$$dX_e/dt = [f'D/P].X_a \qquad (2.3.15)^*$$

$$O_c = [(1-PY_h)(A + C)].X_a \qquad (2.3.16)^*$$

These equations apply also to an anoxic environment provided the following adjustments are made:

(1) Equation (2.3.16) describing the oxygen utilization rate in an anoxic environment needs adjustment in order to express the utilization rate in terms of nitrate instead of oxygen, i.e.

$$(dN_n/dt) = -(1-PY_h)(A+C).X_a/2,86 \qquad (2.3.17)^*$$

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*The meaning of symbols in the equation is given by a list of symbols given before Chapter 1.

(2) The utilization rate of particulate substrate under anoxic conditions has been shown earlier to be lower than that under aerobic conditions. This is incorporated into the general model by including an adjustment constant, η, linking the slowly biodegradable substrate utilization rate constant in the *aerobic* reactor to that in the *anoxic* reactor, i.e. Eq. (2.3.17) is modified to

$$(dN_n/dt) = -(1-PY_h)\ (A+C').X_a/2{,}86 \qquad (2.3.18)^*$$

where

$$C' = \eta.C = \frac{K'_{mpT}}{K_{mpT}}.C \qquad (2.3.19)^*$$

and K'_{mpT} is defined as the slowly biodegradable substrate utilization rate constant under anoxic conditions [mg COD.mg $VSS^{-1}.d^{-1}$].

In effect, apart from the convenient changes from oxygen to nitrate, only one significant change was made - the reduction of K_{mpT} to K'_{mpT}. No structural kinetic changes were made to the model.

In the light of the above modificiations made in order to incorporate the denitrification behaviour in the general model, it is now possible to interpret the significance of the empirical constants discussed in Section 2.3.4 in terms of parameters involved in the general model.

2.3.6 Interpretation of the empirical approach to denitrification

From Section 2.3.5 it follows that in terms of the bi-substrate death-regeneration model, the rate of nitrate utilization dN_n/dt, can be viewed to be comprised of a rate associated with the utilization of easily biodegradable material, dN_1/dt, and a rate associated with the utilization of slowly biodegradable material, dN_2/dt, i.e.

$$dN_n/dt = dN_1/dt + dN_2/dt \qquad (2.3.20)$$

where

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*The meaning of symbols in the equation is given by a list of symbols given before Chapter 1.

$$dN_1/dt = -[(1-PY_h).A/2,86].X_a \qquad (2.3.21)$$

$$\text{and } dN_2/dt = -[(1-PY_h).C'/2,86].X_a \qquad (2.3.22)$$

In Eq. (2.3.6), ΔN_1 and ΔN_2 are the corresponding empirical equations of Eqs. (2.3.21 and 2.3.22) respectively. If "A" is substituted from Eq. (2.3.7) into Eq. (2.3.21) and "C" is substituted from Eq. (2.3.19) into Eq. (2.3.22) respectively, the significance of the empirical K_{1T} and K_{2T} respectively, in denitrification as interpreted by the general model may be given by

$$K_{1T} = [(1-PY_h)K_{msT}.S_{bs}/(K_{ss}+S_{bs})]/2,86 \qquad (2.3.23)$$

$$\text{and } K_{2T} = [(1-PY_h).K'_{mpT}.P.X_s/(P.X_s+K_{spT}.X_a)]/2,86 \qquad (2.3.24)$$

With regard to the utilization of influent easily biodegradable substrate (S_{bsi}) that is implied by Eq. (2.3.23), in a pre-denitrification reactor normally all the influent easily biodegradable substrate is completely utilized and hence knowledge of the exact value of K_{1T} is consequential only in so far as the rate of reaction is concerned but is inconsequential in so far as the *mass* of denitrified nitrate associated with the utilization of easily biodegradable material is concerned. This mass of nitrate removed can be expressed as

$$\Delta N_1 = (1-PY_h).S_{bsi}/2,86 \qquad (2.3.25)$$

Equation (2.3.25) implies that for all practical purposes the nitrate removal due to utilization of easily biodegradable material depends solely on the value of S_{bsi} which is linked to the value of f_{ca} as follows:

$$f_{ca} = S_{bsi}/S_{bi} = S_{bsi}/[S_{ti}(1-f_{us}-P.f_{up})]$$

and the value of K_{msT} in Eq. (2.3.23) is of minor significance.

With regard to the utilization of slowly biodegradable substrate (S_{bp}) that is implied by Eq. (2.3.24), the nitrate removal due to utilization of slowly biodegradable material depends on the value of K'_{mpT} which in turn is linked to K_{mpT} by η.

2.3.7. Identification of the kinetic constants that most significantly affect denitrification

Van Haandel, Ekama and Marais, in a paper to be published

in Water Research (1981), compared the experimental and simulated response of an anoxic-aerobic series reactor system under cyclic loading conditions. They found that they could always obtain very good correlation [see Fig. 2.8(a and b)] provided it was accepted that some of the constants were affected by the influent sewage characteristics. Now, either the theory is not adequate or necessarily the constants are specific to a sewage. If the latter, then this implies that for every sewage it will be good practice to measure the constants. With regard to the former, the wide range of experiments presented by Van Haandel and Marais and the generally good qualitative consistencies obtained between observed and simulated data, provide powerful evidence that the basic kinetic description is adequate. Hence the problem develops in determining the constants for each specific waste flow. However not all the constants need to be determined with equal accuracy. By simulation, using various values for the denitrification constants, Van Haandel and Marais found that the response of the plant is very sensitive to the magnitudes of some of the constants and not so for others. Consequently those that have a sensitive effect should be determined more reliably than those having a relatively insensitive influence. The significant constants appear to be the following:

(1) The slowly biodegradable (particulate) substrate utilization rate constant, K_{mpT}.

(2) The ratio of slowly biodegradable substrate utilization rate constant under anoxic conditions to that under aerobic conditions, $K'_{mpT}/K_{mpT} = \eta$.

(3) The easily biodegradable COD fraction of the influent, $f_{ca} = S_{bsi}/S_{bi}$.

(4) The easily biodegradable substrate utilization rate constant, K_{msT}.

Accurate estimation of the denitrification constants is quite complex because a particular response may be significantly affected by some or all the other constants and it is often difficult to isolate the effects of one constant. This is apparent, in

particular, in plug flow reactor response under constant flow and load wherein the effects of the different reactions have led to the establishment of empirical constants K_{1T}, K_{2T} and K_{3T}. [see Section 2.3.4].

2.3.8 Determination of f_{ca}, K_{mpT} and η

The factors affecting denitrification have been identified in the previous section as

(1) Nitrate removal associated with utilization of easily biodegradable material, i.e. f_{ca}, and

(2) Nitrate removal associated with utilization of slowly biodegradable material, i.e. K_{mpT} and η.

Dold, Ekama and Marais (1980) evaluated f_{ca} by imposing square wave cyclic load conditions (12 hours on 12 hours off) on a single completely mixed aerobic reactor operating at a sludge age of about 2,5 days. At this sludge age the rate of nitrification and the rate of utilization of slowly biodegradable material is virtually negligible compared to the rate of utilization of easily biodegradable material. The precipitous drop in oxygen uptake rate at feed cessation, ΔO, is solely due to the termination of the synthesis associated with the easily biodegradable COD fraction. Hence f_{ca} is given by

$$f_{ca} = \frac{\Delta O}{(1-PY_h)} \cdot \frac{1}{S_{bi}} \cdot \frac{V}{Q_a}$$

where

V = Volume of process (single completely mixed reactor)[ℓ]

Q_a = Actual volumetric flow rate during feeding period [$\ell.h^{-1}$]

$S_{bi} = S_{ti}(1-f_{us}-P.f_{up})$ = Influent biodegradable COD [mg COD.ℓ^{-1}]

ΔO = The precipitous drop in oxygen uptake rate at feed cessation [mg O.ℓ^{-1}.h^{-1}]

The value of η was determined by Ekama, van Haandel and Marais (1979) who compared the *average* observed experimental denitrification rate with the theoretically predicted equivalent oxygen uptake rate in "pre-aerobic" and "post-aerobic" plug flow

systems, using constants developed from *mean* aerobic system response of plants operated under cyclic flow conditions. The ratio of the slope of equivalent oxygen uptake rate in a *post-denitrification* reactor to the oxygen uptake rate in a comparable "post-aerobic" reactor was found to be $\eta = 0,38$. This ratio was also observed with the denitrification associated with slowly biodegradable substrate utilization in a *pre-denitrification* reactor. Hence the utilization rate constant of slowly biodegradable material in an anoxic reactor was made a fraction $\eta = 0,38$ of that in a comparable aerobic reactor, i.e. $K'_{mpT} = \eta.K_{mpT}$. Hence, K_{2T}, associated with the utilization of slowly biodegradable material in an anoxic reactor becomes dependent on K'_{mpT} [see Eq. (2.3.24)]. Ekama *et al* (1979) assessed the temperature dependency of K_{mpT} to be

$$K_{mpT} = K_{mp20}(1,029)^{T-20} \text{ [mg COD.mg VSS.}^{-1}\text{d}^{-1}\text{]}.$$

The estimation of K_{mpT} was obtained by accepting $\eta = 0,38$ in calibration of a cyclically (square wave) loaded anoxic-aerobic reactor series [Ekama *et al* (1979)]. This approach has not been completely satisfactory. The uncertainty in this approach stems from the marked hydraulic effects of cyclic loading [see Section 2.2.4]. In addition, as K_{mpT} and η act in a mutually interactive manner because ($\eta.K_{mpT} = K'_{mpT}$), the individual effect of either one could not be investigated. In the series system experiments η was empirically accepted as constant and the variation in the denitrification rate was ascribed solely to variations in K_{mpT}.

It is evident from the review above that in order to accurately predict the denitrification behaviour, it is necessary that constants f_{ca}, η and K_{mpT} should be accurately evaluated. Hence there is a need for development of a method that allows reliable determination of these constants. The experimental investigation that leads to a suitable method is reported in Chapter 3.

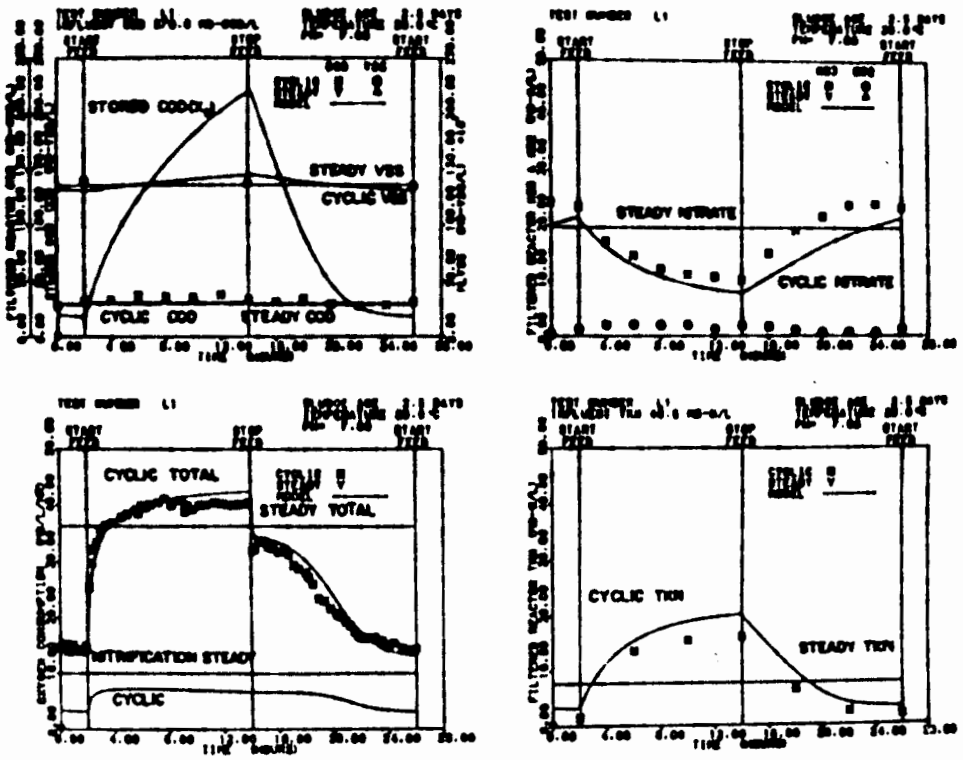

Fig.2.7: Comparison of simulated and observed response of a CMASP under cyclic flow and load with sewage feed using the bi-substrate active-site death-regeneration aerobic model of Dold,Ekama & Marais(1980).

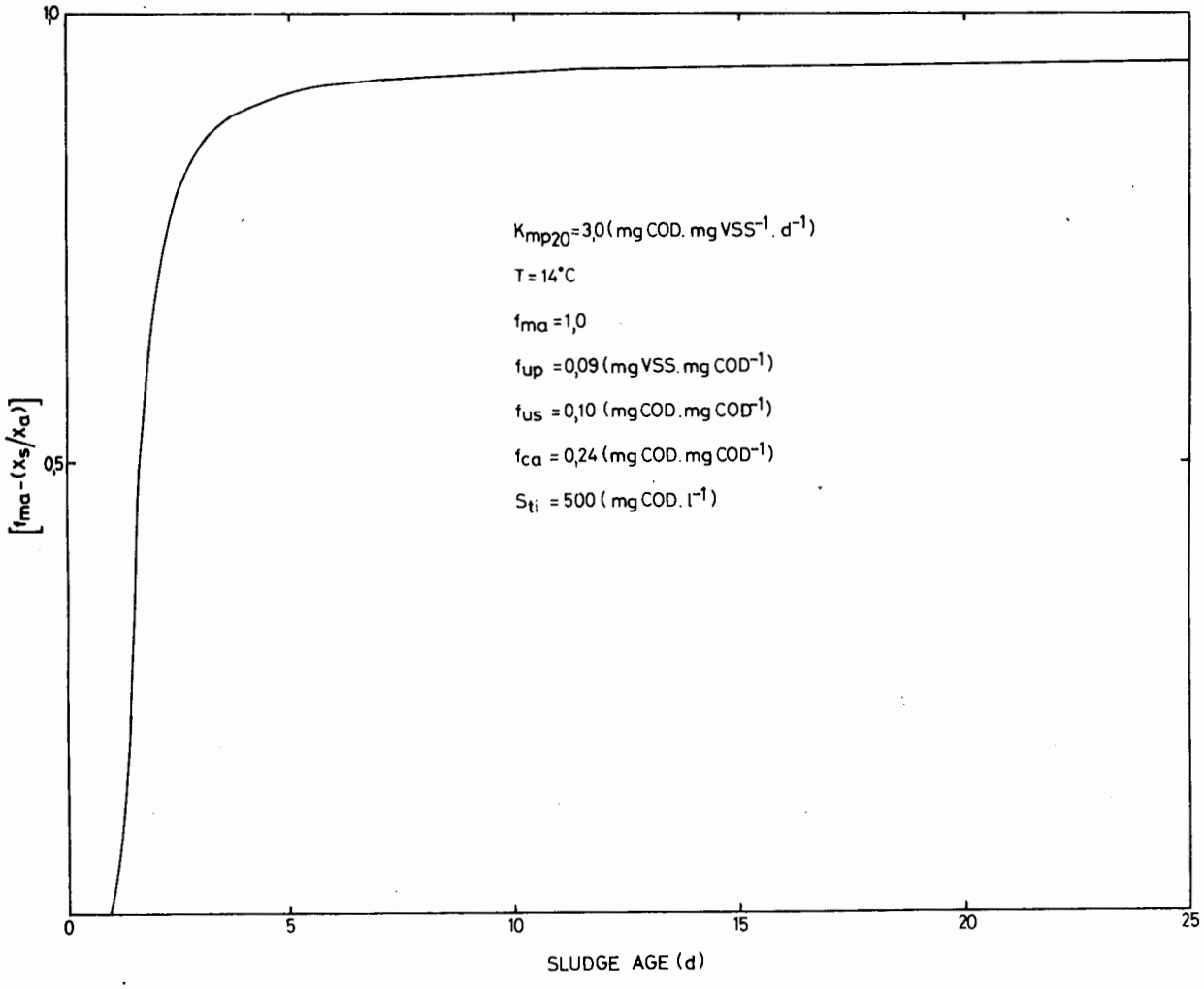

Fig.2.9: Measure of the unoccupied active sites as a function of sludge age.

CHAPTER 3

EXPERIMENTAL INVESTIGATION

3.1 Introduction

The objective of the experimental investigation was to devise experimental set ups and operational procedures which would allow accurate determination of the nitrification and denitrification constants on processes having stable response characteristics. Two approaches towards attaining these objectives were tried. In the first approach a series reactor nitrification-denitrification system was used under constant flow conditions in which the relative volumes of the reactors were chosen such that a sensitive evaluation of the constants should be possible. In the second approach the alternating anoxic-aerobic completely mixed single reactor (CMSR) system under square wave flow and load conditions was investigated.

Series reactor systems had previously been used extensively by Van Haandel, Ekama and Marais [to be published in Water Research (1981)] to determine the constants by calibration. A 3 reactor predenitrification laboratory scale unit was employed (20% predenitrification reactor, 20% first aerobic reactor, 60% second aerobic reactor) and constant and cyclic flow and load conditions, respectively, were imposed. Concurrently a five equal-sized reactor (20% each) pilot scale series predenitrification plant was tested under constant and cyclic flow and load conditions, respectively.

Under cyclic flow and load conditions the observed response on both the 3 and 5 reactor system, respectively, tended to be unstable so that accurate determination of the constants by calibration was not possible. Furthermore the response of the 5 reactor system proved to be more unstable than that of the 3 reactor system. In contrast, under constant flow and load conditions the response was stable indicating that the instability was due to the cyclic nature of the flow and load but which of these contributed the most to the instability could not be ascertained from *observations*.

The response of the system under constant flow and load,

Alternating anoxic-aerobic CMSR system had been investigated at 20°C under *constant* flow and load conditions by Van Haandel and Marais (1981). The response indicated very good stability and good potential for determining the nitrification and denitrification constants. This was confirmed also at 14°C (see section 3.3.3). However this approach required knowledge of the fraction of easily biodegradable influent COD. To determine this fraction required a separate special experimental set up and experimental investigation. The value of alternating anoxic-aerobic approach would be greatly increased if it was possible to determine the easily biodegradable fraction from the same set up as that used for the determination of the other kinetic constants. It was hypothesized that if square wave flow and load pattern was imposed on an alternating anoxic-aerobic CMSR, by suitably choosing the anoxic times within the cycle, it should be possible to determine not only the nitrification and denitrification *kinetic* constants but also the fraction of easily biodegradable influent COD. The second investigation was oriented towards this approach and is discussed in Section 3.3.

3.2 Series System Investigation

In the previous section it was stated that the instability of the response of the 3 reactor series predenitrification system under cyclic flow *and* load was attributed primarily to the cyclic *flow*. It was hypothesized that if the cyclic *flow* were replaced by constant *flow with* an imposed *cyclic TKN load*, a stable response would be obtained that would allow maximum extent of information about *both* nitrification and denitrification.

The major considerations that determined the system configuration and its operational characteristics were:

(a) Information on denitrification can be obtained from an analysis of nitrate removal only if the nitrate entering the anoxic reactor exceeds the denitrification capacity of the reactor, i.e.: the mixed liquor and underflow recycle, respectively must be high enough such that

nitrate is always present in the stream leaving the anoxic reactor.

(b) In order to obtain maximum sensitivity in the data from a reactor the change of the parameter in question must be the maximum possible. In denitrification, the maximum changes will be obtained by having an anoxic reactor as large as possible. However, the anoxic mass fraction in a system cannot be increased *ad lib;* if the anoxic sludge mass fraction exceeds about 40 - 50 percent, poor settling often is encountered to a degree that the system cannot be operated. This has been repeatedly observed by Marsden & Marais (1976) and Arkley & Marais (1981).

(c) Information concerning nitrification and denitrification can be obtained from a predenitrification system. Secondary anoxic reactor has little value as the reduction in nitrate is principally due to endogenous mass loss. For this reason a post-denitrification reactor should be omitted.

Based on the considerations above and by using trial simulation the system configuration selected is shown in Fig. 3.1 and the basic process and sewage parameters listed in Table 3.1.

In Fig. 3.1 the anoxic sludge mass fraction was selected at 40 percent which is the maximum allowable to still retain good settling. To obtain maximum activity in the sludge the shortest practical sludge age was selected. With 40 percent anoxic sludge mass fraction at 14°C, 15 days sludge age was the minimum that allowed continuous and stable nitrification*. The first aerobic reactor was chosen to have a small retention time (about 20 percent of the total process volume). With

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* Later 10 days sludge age was tried, but nitrification consistently declined even with repeated reinocculation of nitrifying sludge. This clearly indicates that 15 days sludge age was a good choice.

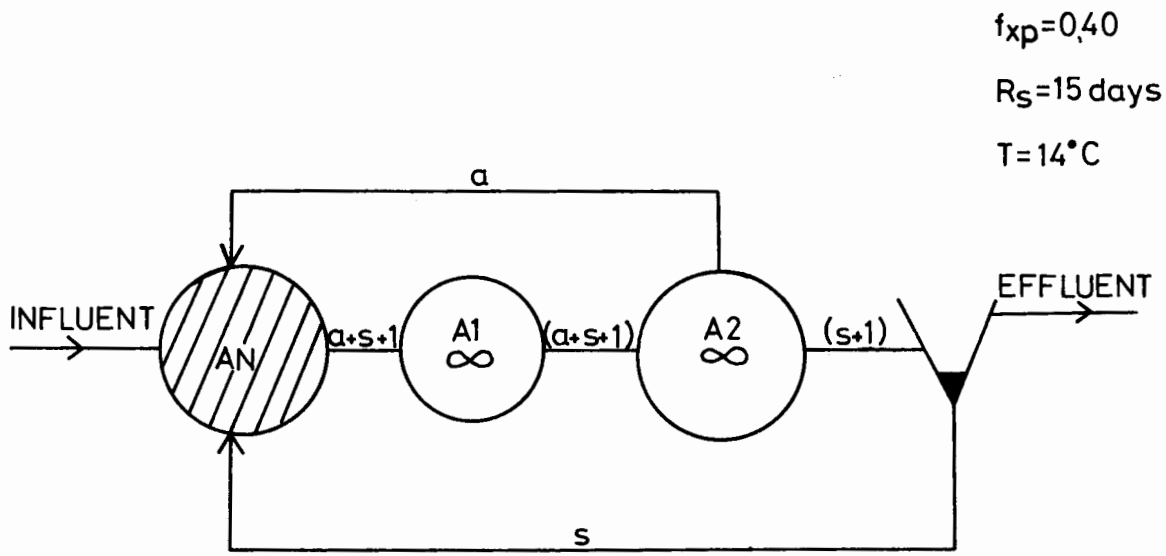

Fig.3.1: Single sludge predenitrification series reactor system employed in the determination of nitrification and denitrification constants.

this fraction it was proposed that the best conditions were available to ensure that:

(1) The maximum nitrification rate constant would be operational and could be determined from the changes in nitrate concentrations.

(2) Any differences in the nitrification rate between the first and the second aerobic reactors would allow investigation of possible effects of the anoxic state on subsequent nitrification.

Table 3.1 *Operational and sewage characteristics used in Fig. 3.1.*

Operational Characteristics :

$T = 14^{\circ}C$

$R_s = 15$ days

Anoxic reactor volume, $V_{AN} = 4{,}67$ [ℓ]

First aerobic reactor volume, $V_{A1} = 2{,}5$ [ℓ]

Second aerobic reactor volume, $V_{A2} = 4{,}5$ [ℓ]

Base feed flow rate, $Q_b = 17{,}2$ [$\ell.d^{-1}$]

Sewage Characteristics :

$f_{up} = 0{,}09$ [mg VSS.mgCOD^{-1}] $f_{na} = 0{,}75$ [mgNH$_3$-N.mgN^{-1}]

$f_{us} = 0{,}15$ [mg COD.mgCOD^{-1}] $f_{nu} = 0{,}0$ [mgN.mgN^{-1}]

3.2.1 Predenitrification series system under constant flow and load conditions.

The series system in Fig. 3.1 was initially run under *constant flow and load.* The objective in operating under constant flow and load was to develop an accurate experimental procedure to ensure that all the process variables were correctly measured so that when a cyclic load was imposed, any operational or analytical uncertainties would have been resolved and attention could be focused on the objective of the investigation - the determination of the magnitude of the kinetic constants in question.

Proper measurement of all process variables is indicated if satisfactory mass balances are achieved on the system operated under constant flow and load. From theoretical mass balance calculations, it was apparent that of all the measurable process variables : COD, VSS, TKN, NO_3, Oxygen Uptake Rate (O.U.R.) and recycle flow rates, inaccurate measurement of the recycle flow rates has the most sensitive effect on the mass balance. The reason for this is that the recycle rates are quite high (a+s=6) so that any error in the measurement of concentration of a parameter involved in the mass balance has a multiplicative effect on the mass balance calculation. Consequently particular attention was given to measuring the recycle flows and checking them daily. The system was run for a period of about two months during which period eight batches of sewage were used and the forementioned process variables measured daily. From the measured process parameters the calculation of mass balances of nitrogen and COD were made. The procedure for calculating the mass balances is set out in detail in Appendix B together with the computer program (program B.1) based on this procedure.

A summary of the average response for each batch of sewage, and the respective nitrogen and COD balances as calculated by the mass balance program is listed in Table 3.2.

Table 3.2 *Average observed response and output of mass balance program for the system in Fig. 3.1 operated under constant flow and load.*

SEWAGE BATCH NO. / CODE**	1	2	3	4	5	6	7*	8*
DATE	21/4-23/4	24/4-2/5	3/5-9/5	10/5-16/5	20/5-22/5	25/5-30/5	31/5-8/6	9/6-13/6
CODIN [mgCOD.ℓ^{-1}]	494,0	493,4	483,6	509,0	506,3	480,4	488,5	489,3
CODOUT[mgCOD.ℓ^{-1}]	37,3	68,4	51,7	71,2	54,0	56,7	52,4	55,5
TKNIN [mgN.ℓ^{-1}]	59,1	55,9	52,4	49,9	49,6	49,2	49,2	50,1
TKNOUT[mgN.ℓ^{-1}]	1,8	3,5	1,5	3,0	2,2	5,1	2,2	3,1
OUR_1[mgO.ℓ^{-1}.h^{-1}]	49,2	43,0	46,8	42,4	37,2	34,4	44,3	48,7
OUR_2[mgO.ℓ^{-1}.h^{-1}]	20,2	18,0	22,4	26,7	25,1	24,2	23,5	21,6
NO_3AN[mgN.ℓ^{-1}]	18,0	14,1	14,1	15,0	10,6	9,8	11,5	10,0
NO_3A2[mgN.ℓ^{-1}]	23,3	18,8	18,8	19,4	15,0	12,9	16,3	14,8
NO_3EFF[mgN.ℓ^{-1}]	22,8	19,7	18,8	21,9	15,8	11,2	16,4	14,9
DNIT [mgN.ℓ^{-1}]	23,0	23,5	22,6	21,9	21,9	14,4	17,6	19,1
NRECOV [%]	98,7	102,8	103,2	117,1	104,1	85,9	98,4	98,1
CODREC [%]	75,9	78,8	87,6	90,6	85,7	91,7	92,8	94,2

* Batch of sewage for which satisfactory mass balances were obtained on both nitrogen and COD. Mass balances were considered satisfactory when mass recoveries of 95 percent and 90 percent or higher for nitrogen and COD mass balance respectively were obtained.

** Code designation is given in the mass balance program (program B.1) in Appendix B under program output variables.

From Table 3.2 it is apparent that initially the mass balances were poor. With time, the procedures for calibrating the recycle pumps were improved and concomitantly more satisfactory balances were achieved, after six weeks of operation (Batch numbers 7 and 8). It was very evident from the mass balance evaluation that in this type of process unless extreme care is taken with the measurement of the recycles, unreliable results are the inevitable consequence.

No attempt was made to determine the nitrification and denitrification constants from the series system under constant flow and load. Two observations supported this decision:

(1) Table 3.2(a) gives the TKN response for batches of sewage that gave satisfactory mass balances. It is apparent that the changes in TKN concentration were small and the TKN response was therefore insensitive to different values of μ_{nmT}. Also, the actual TKN concentrations in the aerobic reactors were usually low because of the dilution effect of the influent TKN by the high mixed liquor recycle, a, and underflow recycle, s, respectively and errors in the concentrations led to large errors when using differences.

(2) The short retention time in the first aerobic reactor, A1, gave rise to small changes in nitrate concentrations entering and leaving the reactor. From experimental data (Table 3.2(b)), for batches of sewage that gave satisfactory mass balances, the average difference in nitrate concentrations entering and leaving A1 is 3,3 [mg NO_3-N.ℓ^{-1}]; considering that the nitrate measurement is only accurate to within 1,0 [mg NO_3-N.ℓ^{-1}], this may result in errors up to 30 percent in the estimation of μ_{nmT}.

Table 3.2(a) *Observed TKN response of the system depicted in Fig.3.1 obtained under constant flow and load for batches of sewage with which satisfactory mass balances were obtained.*

DATE	TKN_{AN} [mgN.ℓ^{-1}]	TKN_{A1} [mgN.ℓ^{-1}]	TKN_{A2} [mgN.ℓ^{-1}]	ΔTKN_{AN-A1} [mgN.ℓ^{-1}]	ΔTKN_{A1-A2} [mgN.ℓ^{-1}]
31/5	4,6	2,4	1,1	2,2	1,3
3/6	7,7	6,2	2,8	1,5	3,4
5/6	7,3	6,3	1,8	1,0	4,5
6/6	6,0	2,5	1,9	3,5	0,6
7/6	5,6	3,2	2,4	2,4	0,8
12/6	6,3	3,6	1,0	2,7	2,6

Subscript AN refers to the anoxic reactor.
Subscript A1 refers to the first aerobic reactor.
Subscript A2 refers to the second aerobic reactor.

The problem generally with the series system operated under constant flow and load is that the observed response is a *net* effect of the reaction rate plus wash-out rate. The wash-out rate, however, usually has a much greater effect principally because of the requirement of high recycle flows. The masking effect of the wash-out rate makes the estimation of the reaction rate difficult to assess accurately and precisely. One way of inducing a high reaction rate is to impose high influent concentrations, but such high concentrations usually cannot be found in domestic waste waters. Alternatively, the wash-out rate could be reduced by reducing the recycle flow rates but this reduction is possible only to that degree that the effluent nitrate from the anoxic reactor, theoretically does not fall below zero. Because zero nitrate concentration arises also if the denitrification capacity exceeds the nitrate entering the reactor, the concentration must be maintained positive, say, not less than 2 [mgN.ℓ^{-1}].

Table 3.2(b) *Observed nitrate response of the system depicted in Fig. 3.1 obtained under constant flow and load conditions for batches with which satisfactory mass balances were obtained.*

Sewage Batch No.	DATE	NO_3AN [$mgNO_3$-N.ℓ^{-1}]	NO_3Al [$mgNO_3$-N.ℓ^{-1}]	ΔNO_3 [$mgNO_3$-N.ℓ^{-1}]	State of Nitrogen and COD Mass Balance on Sewage Batch
	31-5-80	9,9	12,4	2,5	Satisfactory
	2-6-80	11,3	14,1	2,8	
7	6-6-80	10,6	14,4	3,8	N-Balance=98,4%
	7-6-80	12,7	16,6	3,9	CODBalance=92,8%
	8-6-80	12,9	16,9	4,0	
	9-6-80	8,1	11,7	3,6	Satisfactory
	10-6-80	9,4	12,8	3,4	
8	11-6-80	11,4	14,4	3,0	N-Balance=98,1%
	12-6-80	11,4	14,6	3,2	CODBalance=94,2%
	13-6-80	9,5	12,5	3,0	
Average:		10,7	14,0	3,3	

The remarks on the previous page illustrate the inadequacies and limitations of the series system under *constant flow and load* to determine kinetic effects accurately. However, the series of experiments did contribute in verifying the limitations of the system and allowed the establishment of reliable experimental procedures.

3.2.2 Predenitrification series system under constant flow and COD load and with an imposed TKN pulse.

In the previous section it was shown that the marked hydraulic effects of the recycle flows led to small relative changes in the measurable nitrification-denitrification process variables (TKN, NO_3).

It was hypothesized that if a high TKN concentration slug was introduced, transient conditions would be set up such that the relative changes of the measurable nitrification-denitrification process variables (TKN, NO_3) would be large enough to effect accurate determination of the nitrification and denitrification constants despite the marked hydraulic effects of the recycle flows. This could be achieved by using a system configuration identical to that used in the constant flow and load experiment (Fig. 3.1) and imposing a cyclic load by feeding a very small flow of high TKN concentration (TKN pulse) once a day over a fixed period of time. The TKN pulse was introduced at a constant rate directly into the anoxic reactor for a period of 4 hours at a fixed time (16.00 hours) each day.

Details of the method of feeding the TKN pulse are as follows: An ammonium chloride stock solution was prepared such that it would effect a known contribution of ammonia to the base load over the 4 hour period. The total mass of TKN entering via the base flow, Q_b = 17,2 [$\ell.d^{-1}$], with a TKN concentration of approximately 50[mgN.ℓ^{-1}] is 17,2.50 = 860 [mg N.d^{-1}]. It was suggested that if the TKN pulse should contribute an additional load of approximately a third of the daily base TKN load i.e. about 280 [mg N.d^{-1}], transient conditions would be set up such that the observed changes in the TKN and nitrate concentrations between the reactors would be large enough to effect accurate determination of the nitrification and denitrification constants. The contribution of the stock solution over the 4 hour pulse feeding period depends on the pulse feeding rate, V_r. The stock solution was prepared to effect a contribution of 280 mgN over the 4 hour pulse feeding period as follows: 1000 mls. of nitrogen stock solution was prepared to contain $280 \cdot 1000/V_r = 280 \cdot 1000/50{,}20$ [mg N.ℓ^{-1}]; V_r = measured TKN *pulse* flow rate *over the 4 hour* feeding period = 50,20 [mls/4 hours]. The TKN pulse contribution *per hour*, ΔTKN, to the base TKN concentration was now given by

$$\Delta TKN = \frac{280}{4} \cdot \frac{1}{Q_b + V_r \cdot \frac{4}{1000}} \qquad (3.1)$$

where Q_b = Volumetric Base feed flow rate [$\ell.h^{-1}$]

but $Q_b >> V_r \cdot 4/1000$

Hence the TKN pulse contribution *per hour* was given approximately by

$$\Delta TKN = \frac{280}{4} \cdot \frac{1}{Q_b} \qquad (3.2)$$

In the first test (see Fig. 3.2a), the pulse rate was measured to be V_r = 50,20 [mls/4 hours] so that Eq. (3.2) could be used directly in calculating the TKN pulse contribution per hour to the base TKN concentration. In a subsequent test a week later the TKN pulse feeding rate was rated at V_r = 60,0 [mls/4 hours] so that Eq. (3.2) had to be multiplied by 60,0/50,20 to account for the increased V_r.

In order to allow adaption of the process to the additional TKN feed, the system was run for a week before monitoring of process variables commenced. Thereafter monitoring was done once a week over 24 hours; each of the process variables (COD, TKN, NO_3 of all the reactors and oxygen uptake rate of each of the aerobic reactors) was measured every 2 hours. This was repeated every week until the process exhibited a stable response pattern. Tables 3.3 (a and b) show the response of two such consecutive weeks, indicating, in particular, that the autotrophic behavioural pattern had achieved an apparent dynamic steady state.

Comparison of experimentally observed results with the simulation, using the general model for a *square wave cyclic* TKN input is shown in Figs.3.2 (a and b). The appropriate simulated results shown are the outcome of a rather tedious trial and error procedure whereby K_{mpT}, η, f_{ca} and μ_{nmT} were each changed in turn, keeping all other parameters unchanged until the closest possible agreement with experimental observations was effected. The correlation achieved however, is not good, in particular, the experimental nitrate profiles in both Figs. 3.2 (a and b) - the system did not exhibit a consistent cyclic behaviour. This anomalous behaviour

possibly can be ascribed to two effects acting in opposition caused by the TKN pulse. On the one hand the imposed TKN pulse gives rise to high TKN and nitrate concentrations which increases the reliability of their respective differences in the influent and effluent of a reactor. This would increase the reliability of the evaluation of μ_{nmT}. On the other hand, the cyclicity of, say, the nitrate is still contributory to an accumulative error effect associated with the TKN pulse: A slight error in the TKN pulse flow rate of, say, 10 mls in 4 hours (1 ml contains approximately 6 mgN) significantly affects the system's nitrate response; the slightest error in the pumping rate disproportionately distorts the effluent quality from the mean behaviour. Unfortunately the pumping system employed could not guarantee a high accuracy in the flow rate, particularly due to fluctuations in the supplied voltage to the pump.

Reviewing the approach it would appear that despite the theoretical advantages of the system, the practical problem of ensuring extremely accurate measurement of the TKN pulse feeding rate (as well as the recycles' rates) still resulted in unreliable estimates of μ_{nmT}. Furthermore, to fit the simulations to the data was so time consuming that it tended to the point of impracticability. Although feasible, the approach was discarded as not being of a simple enough practical nature for determining μ_{nmT}.

Table 3.3(a) *Observed response of the system in Fig. 3.1 under a constant COD load and a square wave TKN (pulse) load. (Test No. 1) at 14°C, R_s = 15 days.*

Time [h]	Anoxic reactor (AN) response		Aerobic reactor (A1) response		Aerobic reactor (A2) response		Time [h]	Ox. uptake rate in A1 [mg $O.\ell^{-1}h^{-1}$]	Time [h]	Ox. uptake rate in A2 [mg $O.\ell^{-1}h^{-1}$]
	TKN [mg $N.\ell^{-1}$]	NO_3 [mg $N.\ell^{-1}$]	TKN [mg $N.\ell^{-1}$]	NO_3 [mg $N.\ell^{-1}$]	TKN [mg $N.\ell^{-1}$]	NO_3 [mg $N.\ell^{-1}$]				
14,00	7,8	22,7	4,5	26,8	2,5	28,0	14,2	54,0	14,3	21,2
*16,00	7,7	20,3	3,5	24,6	3,1	26,4	16,2	60,2	16,2	23,7
18,00	22,4	21,1	12,5	26,1	4,1	30,1	18,1	61,8	18,3	49,2
**20,00	30,2	23,3	16,9	28,3	8,1	32,8	20,1	61,7	21,2	43,0
22,00	15,1	25,2	11,8	28,8	7,4	34,4	22,1	58,3	22,7	39,1
24,00	12,3	27,4	8,7	30,2	4,8	34,4	24,1	56,0	24,5	33,3
2,00	9,4	26,5	5,5	32,0	4,1	34,8	2,1	53,7	2,2	25,7
4,00	9,5	26,7	3,6	30,6	3,2	32,8	3,8	55,5	3,8	21,0
6,00	-	25,2	-	28,6	-	30,7	5,5	55,5	5,7	24,8
8,00	7,8	23,6	2,9	27,7	2,7	29,1	7,5	58,4	7,8	22,6
10,00	6,9	21,3	3,1	27,4	3,1	26,5	9,5	49,3	9,7	19,8
12,00	8,4	-	2,7	-	2,5	-	11,5	54,0	11,7	21,2
14,00	7,0	20,4	2,4	23,6	1,3	24,5	13,5	53,3	13,7	20,2

Influent COD = 522,7 [mg $COD.\ell^{-1}$] Influent (base) TKN = 55,4 [mg $N.\ell^{-1}$] * begin TKN pulse ** end TKN pulse

TKN concentration during pulse feeding period = $55,4 + \frac{280}{4} \cdot \frac{24}{17,2} = 153,1$ [mg $N.\ell^{-1}$]

Table 3.3(b) *Observed response of the system in Fig. 3.1 under a constant COD load and a square wave TKN (slug) load (Test No. 2) at 14°C, R_s = 15 days.*

Time [h]	Anoxic reactor (AN) response		Aerobic reactor (A1) response		Aerobic reactor (A2) response		Time [h]	Ox. uptake rate in A1 [mg $O.\ell^{-1}h^{-1}$]	Time [h]	Ox. uptake rate in A2 [mg $O.\ell^{-1}h^{-1}$]
	TKN [mg $N.\ell^{-1}$]	NO_3 [mg $N.\ell^{-1}$]	TKN [mg $N.\ell^{-1}$]	NO_3 [mg $N.\ell^{-1}$]	TKN [mg $N.\ell^{-1}$]	NO_3 [mg $N.\ell^{-1}$]				
14,00	7,4	36,3	-	41,4	2,2	43,0	14,2	52,3	14,3	17,4
*16,00	7,8	36,8	3,7	40,5	3,1	42,3	16,1	55,1	16,3	22,1
18,00	16,4	35,7	9,1	40,8	-	43,0	18,1	56,4	18,5	40,8
**20,00	19,3	38,5	14,7	42,2	6,9	47,5	20,1	57,7	20,2	53,2
22,00	12,8	40,7	7,2	43,9	4,4	49,5	22,9	56,6	23,0	40,5
24,00	8,8	40,7	4,4	46,0	3,5	48,3	24,1	56,6	24,3	25,2
2,00	8,1	39,9	-	43,9	-	46,0	2,1	56,3	2,3	21,5
4,00	-	35,5	-	42,2	-	43,5	4,1	55,5	4,4	21,9
6,00	6,9	35,7	-	40,0	4,4	41,5	6,1	54,8	6,2	19,0
8,00	6,3	34,3	5,2	-	-	39,7	8,1	57,2	8,2	19,4
10,00	5,9	31,8	-	37,3	2,7	37,3	10,1	60,2	10,3	18,7
12,00	-	30,0	2,2	34,8	4,3	36,0	12,1	52,5	12,4	20,6
14,00	8,4	29,8	-	33,6	3,7	35,0	14,4	49,8	14,8	21,5

Influent COD = 467,6 Influent (base) TKN = 57,0 [mg $N.\ell^{-1}$] * begin TKN pulse ** end TKN pulse

TKN influent concentration during pulse feeding period = $57,0 + \frac{280}{4} \cdot \frac{60,0}{50,20} \cdot \frac{24}{17,2} = 173,7$ [mg $N.\ell^{-1}$]

Table 3.3(b) *Observed response of the system in Fig. 3.1 under a constant COD load and a square wave TKN (slug) load (Test No. 2) at 14°C, R_s = 15 days.*

Time [h]	Anoxic reactor (AN) response		Aerobic reactor (A1) response		Aerobic reactor (A2) response		Time [h]	Ox. uptake rate in A1 [mg O.$\ell^{-1}h^{-1}$]	Time [h]	Ox. uptake rate in A2 [mg O.$\ell^{-1}h^{-1}$]
	TKN [mg N.ℓ^{-1}]	NO_3 [mg N.ℓ^{-1}]	TKN [mg N.ℓ^{-1}]	NO_3 [mg N.ℓ^{-1}]	TKN [mg N.ℓ^{-1}]	NO_3 [mg N.ℓ^{-1}]				
14,00	7,4	36,3	-	41,4	2,2	43,0	14,2	52,3	14,3	17,4
*16,00	7,8	36,8	3,7	40,5	3,1	42,3	16,1	55,1	16,3	22,1
18,00	16,4	35,7	9,1	40,8	-	43,0	18,1	56,4	18,5	40,8
**20,00	19,3	38,5	14,7	42,2	6,9	47,5	20,1	57,7	20,2	53,2
22,00	12,8	40,7	7,2	43,9	4,4	49,5	22,9	56,6	23,0	40,5
24,00	8,8	40,7	4,4	46,0	3,5	48,3	24,1	56,6	24,3	25,2
2,00	8,1	39,9	-	43,9	-	46,0	2,1	56,3	2,3	21,5
4,00	-	35,5	-	42,2	-	43,5	4,1	55,5	4,4	21,9
6,00	6,9	35,7	-	40,0	4,4	41,5	6,1	54,8	6,2	19,0
8,00	6,3	34,3	5,2	-	-	39,7	8,1	57,2	8,2	19,4
10,00	5,9	31,8	-	37,3	2,7	37,3	10,1	60,2	10,3	18,7
12,00	-	30,0	2,2	34,8	4,3	36,0	12,1	52,5	12,4	20,6
14,00	8,4	29,8	-	33,6	3,7	35,0	14,4	49,8	14,8	21,5

Influent COD = 467,6 Influent (base) TKN = 57,0 [mg N.ℓ^{-1}] * begin TKN pulse ** end TKN pulse

TKN influent concentration during pulse feeding period = $57,0 + \frac{280}{4} \cdot \frac{60,0}{50,20} \cdot \frac{24}{17,2} = 173,7$ [mg N.ℓ^{-1}]

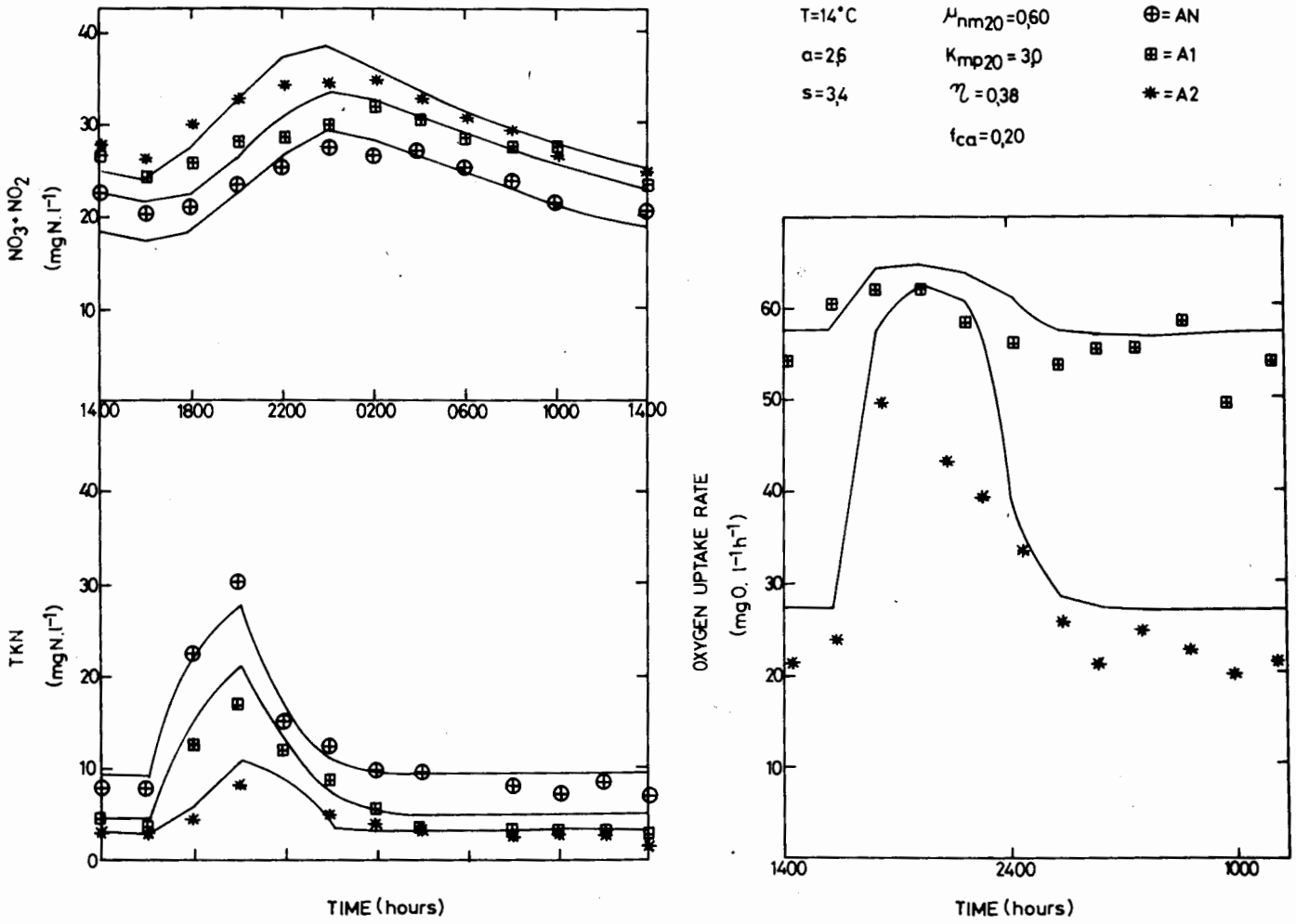

Fig.3.2a: Closest fit of the observed response of the series system in Fig.3.1 under a constant COD load and with a square wave TKN load at 14°C, R_s=15 days (Experiment No. 1).

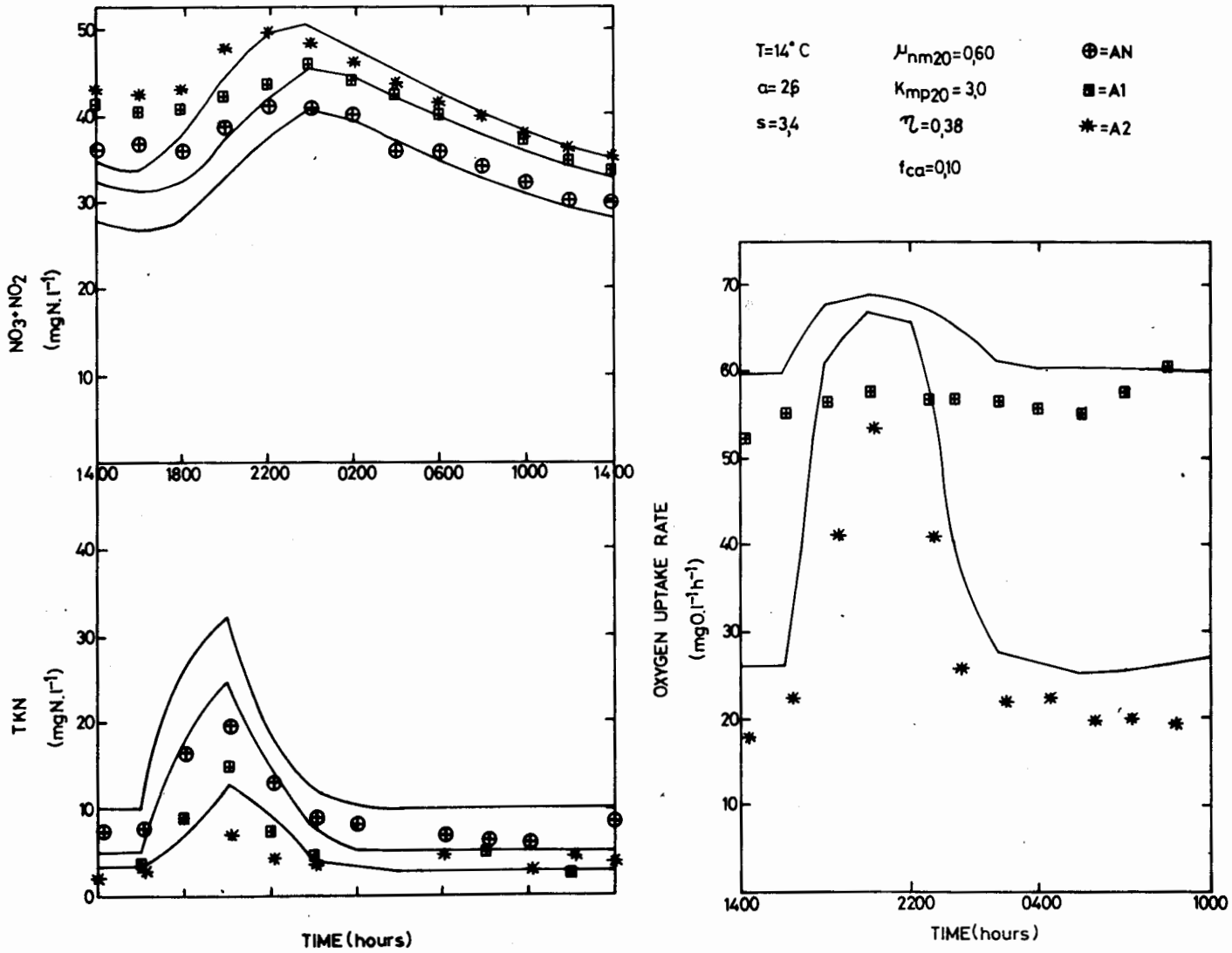

Fig.3.2b: Closest fit of the observed response of the series system in Fig.3.1 under a constant COD load and with a square wave load of TKN at 14°C, R_s=15 days (Experiment No. 2).

3.3. Completely Mixed Single Reactor (CMSR) System.

3.3.1 Estimation of reaction rates in CMSR system

The observed rate of change in any system is the *net* effect of the rate of reaction together with the hydraulic washout rate. In a CMSR the hydraulic effect can be easily accounted for, thereby allowing determination of the nitrification and denitrification *reaction rates* and, hence, the associated kinetic constants :

Van Haandel and Marais (1981) showed that over the interval (t_2-t_1) the average reaction rate of concentration C in a reactor j, $^{r}C_{jr}$ is given by

$$^{r}C_{jr} = (C_{jt2}-C_{jt1})/(t_2-t_1) - (\overline{C}_{ij}-\overline{C}_j)/R_j \qquad (3.3)$$

where

C_{jt2} = Concentration of C in reactor j at time t_2

C_{jt1} = Concentration of C in reactor j at time t_1

$\overline{C}_j = (C_{jt1} + C_{jt2})/2$

$\overline{C}_{ij}$ = Average concentration of C in the influent to reactor j over the interval (t_2-t_1).

R_j = Actual hydraulic retention time in reactor j during the interval (t_2-t_1)

Considering the nitrification rate ($C=NO_3$) in a CMSR system (j=1), with feed that is free of nitrate ($\overline{C}_{ij}=0$), Eq (3.3) may be reduced to

$$^{r}[NO_3]_r = ([NO_3]_{t2} - [NO_3]_{t1})/(t_2-t_1) + [\overline{NO_3}]/R_h \qquad (3.4)$$

where

$[\overline{NO_3}] = ([NO_3]_{t1}+[NO_3]_{t2})/2$

R_h = Actual hydraulic retention time in the CMSR during the interval (t_2-t_1)

Equation (3.4) is used to evaluate the average nitrification *reaction* rate from the nitrate-time response curve observed on a CMSR system during an aerobic period.

Considering the denitrification rate during an anoxic period over any time interval (t_2-t_1), the average denitrification reaction rate is obtained from the nitrate-time response curve as follows:

Equation (3.4) is rewritten

$$-r[NO_3]_r = -([NO_3]_{t_2} - [NO_3]_{t_1})/(t_2-t_1)-[\overline{NO_3}]/R_h$$

i.e.

$$-r[NO_3]_r = ([NO_3]_{t_1} - [NO_3]_{t_2})/(t_2-t_1)-[\overline{NO_3}]/R_h \qquad (3.5)$$

From the development above these equations are valid for any flow condition, constant or varying with time, provided that during variable flow the value of R_h over the interval (t_2-t_1) is available.

3.3.2. Alternating anoxic-aerobic CMSR (AAACMSR) system under square wave flow and load

In Section 3.1 it was hypothesized that when a square wave flow and load pattern is imposed on an alternating anoxic-aerobic CMSR (AAACMSR) system, it should be possible to determine *all* the constants affecting nitrification and denitrification i.e. μ_{nmT}, f_{ca}, K_{mpT} and η. To test this, an experimental set up identical to that given in Fig 3.3 was employed with operational and sewage characteristics as listed in Table 3.4. A daily cyclic square wave input flow (12 h feed, 12 h no feed) was imposed with a single anoxic period of 2 h duration each day during the high flow period. This was done by switching the electrical current, to an air pump, on and off. The plant was operated in this fashion until, apparently, steady state conditions were achieved. During this period the VSS and mean effluent TKN were checked daily; it was presumed that when these showed no change, steady state had been achieved.

Once steady state had been achieved, intensive testing was done over that fraction of anoxic-aerobic period during which rapid changes of concentrations of nitrate, alkalinity, TKN and NH_3 took place. Samples were taken every hour and the following process variables monitores: Oxygen uptake rate, COD, VSS, TKN, NH_3, NO_3 and Alk.

Two experiments were carried out under square wave flow and load on the AAACMSR system using the *same* sewage batch. In the first experiment (EST 31), the 2 h anoxic period was introduced 1 hour after the beginning of the feeding period; the observed response is listed in Table 3.5a. In the second experiment (EST 32), the 2 h anoxic period was introduced 2 hours after the beginning of the feeding period; the observed response is listed in Table 3.5b. This data provided the basis for inquiring into the determination, by manual means, of the kinetic nitrification and denitrification constants.

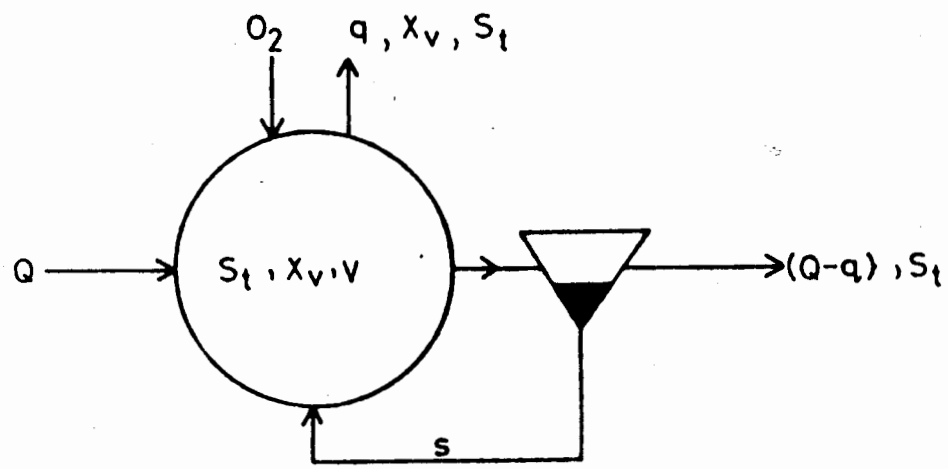

Fig.3.3: Completely mixed single reactor (CMSR) system used in the determination of nitrification and denitrification constants by imposing alternating anoxic-aerobic conditions.

Table 3.4 *Operational and average sewage characteristics used in Fig. 3.3 operated under daily square wave conditions with a single anoxic period of 2 hours in 24.*

Operational Characteristics

T = 14°C

Reactor volume, V = 15 [ℓ]

Feeding period, t_f = Non feeding period = 12 [h]

Hydraulic retention time during feeding period = 6 [h]

Sludge age, R_h = 15 [d]

Duration of stable*operation before testing commenced = 14 [d]

Sewage Characteristics

		Average**
Influent COD =	468 to 572 [mg COD.ℓ^{-1}]	507 [mg COD.ℓ^{-1}]
Influent TKN =	48 to 51 [mg N.ℓ^{-1}]	49 [mg N.ℓ^{-1}]

f_{ca} = 0,10 [mg COD.mg COD^{-1}] (determined from an independent experimental setup)

f_{up} = 0,09 [mg VSS.mg COD^{-1}]

f_{us} = 0,12 [mg COD.mg COD^{-1}]

f_{na} = 0,64 [mg NH_3-N.mg N^{-1}]

f_{nu} = 0,0 [mg N.mg N^{-1}]

* Stable operation characteristic to steady state conditions is indicated by a constant VSS and consistent nitrification with a corresponding constant mean effluent TKN.

** Disregarding any outliers.

Table 3.5a *Observed response of a CMSR system under square wave flow and load (experiment EST 31) at 14°C, R_s = 15 days, pH = 7,2*

SAMPLE	TIME [h]	NH_3 [mgN.ℓ^{-1}]	TKN [mgN.ℓ^{-1}]	NO_3 [mgN.ℓ^{-1}]	ALKALINITY [mg$CaCO_3$.ℓ^{-1}]	COD [mgCOD.ℓ^{-1}]	VSS [mgVSS.ℓ^{-1}]	TIME [h]	O.U.R. [mgO.ℓ^{-1}.h^{-1}]
Influent		27,0	51,9	0,0	413,0	503,0	-	-	-
Effluent		2,51	6,2	23,8	213,0	59,8	-	-	-
1	6,00	0,41	5,5	29,5	185,4	-	3488,0	6,1	15,3
2	8,00 *	0,10	5,5	30,0	183,3	56,2	-	7,0	16,5
3	9,00 ***	1,1	5,3	30,0	187,5	76,6	3351,0	8,1	39,4
4	10,00	4,6	10,5	20,4	222,0	-	3346,0	9,0	46,5
5	11,00 ****	8,3	14,0	15,7	252,4	73,3	3394,0	11,1	47,8
6	13,00	5,1	6,4	19,2	230,2	-	3351,0	12,1	55,3
7	16,00	0,5	4,8	27,7	185,4	70,4	3395,0	13,1	53,0
8	19,00	0,4	-	28,3	181,3	-	-	14,6	52,6
9	20,00 **	0,2	5,2	-	181,3	55,0	3560,0	16,1	43,8
10	21,00	0,17	3,4	28,35	180,2	68,4	3665,0	18,0	43,8
11	22,00	0,05	2,4	28,4	174,1	59,5	3644,0	19,1	43,8
								20,2	44,4
								20,3	25,1
								20,5	21,3
								20,7	19,5
								22,0	16,0

* begin feeding period
** end feeding period
*** begin anoxic period
**** end anoxic period

Table 3.5b *Observed response of a CMSR system under square wave flow and load (experiment EST 32) at 14°C, R_s = 15 days, pH = 7,2*

SAMPLE	TIME [h]	NH_3 [mgN.ℓ$^{-1}$]	TKN [mgN.ℓ$^{-1}$]	NO_3 [mgN.ℓ$^{-1}$]	ALKALINITY [mgCaCO$_3$.ℓ$^{-1}$]	COD [mgCOD.ℓ$^{-1}$]	VSS [mgVSS.ℓ$^{-1}$]	TIME [h]	O.U.R. [mgO.ℓ$^{-1}$.h^{-1}]
Influent		32,6	51,2	0,0	412,0	492,8			
Effluent		3,4	6,7	25,0	208,1	69,0			
1	7,00	0,37	-	29,5	173,6	50,7	3642,0	7,1	13,4
2	8,00*	0,28	3,1	30,6	173,6	-	-	8,0	28,8
3	9,00	0,69	3,6	30,3	172,0	-	3393,0	8,4	38,8
4	10,00***	-	2,9	30,3	-	52,7	3482,0	8,7	46,6
5	11,00	5,82	9,2	22,8	210,1	62,9	3419,0	8,9	46,7
6	12,00****	9,42	12,6	16,3	247,2	69,0	3472,0	9,1	44,5
7	13,00	8,15	-	17,8	240,5	64,9	3366,0	9,4	42,5
8	14,00	5,63	5,6	20,7	225,1	64,9	3429,0	10,0	41,7
9	16,00	1,34	4,8	25,5	191,1	-	3451,0	12,1	50,8
10	19,00	0,79	3,5	28,8	177,2	-	-	13,1	59,4
11	20,00**	0,51	3,4	29,1	173,0	64,9	3502,0	14,1	53,3
12	21,00	1,07	3,2	29,4	172,5	-	3518,0	16,2	54,2
13	22,00	0,42	4,6	-	175,6	-	-	19,1	44,3
								20,1	40,8
								20,4	18,0
								21,2	16,5

* begin feeding period
** end feeding period
*** begin anoxic period
**** end anoxic period

3.3.2a Manual determination of μ_{nmT}, f_{ca}, K_{mpT} and η from a CMSR system under a square wave flow feeding pattern

One important object of a CMSR system operated under a square wave input pattern, and subjected to alternating anoxic-aerobic conditions during the high flow period, was to check if it is possible to estimate all the constants that significantly affect nitrification and denitrification *without* the aid of a computer. It is now the intention to describe the procedures by means of which such estimates can be made. The estimation of each of the constants from the experimental response of experiment EST 32 will be dealt with separately.

3.3.2a(I) Estimation of μ_{nmT}

The maximum nitrification rate constant, μ_{nmT}, can be readily estimated from the nitrate profile of the aeration period subsequent to the anoxic period. During this period it can be accepted that the ammonia concentration remains so high (above 2 [mg $N.\ell^{-1}$]) that the nitrification rate constant μ_{nT} will be maintained at its maximum value, μ_{nmT}, given by

$$\mu_{nmT} = Y_n \, (dN_n/dt)/X_n$$

To evaluate μ_{nmT} the value of X_n needs to be calculated: it was shown in Section 2.2.3 that in order to calculate X_n the values of Y_n and b_{nT} must be known. Accepting the standard values for Y_n and b_{nT} (i.e. $b_{n20} = 0{,}04[d^{-1}]$, $Y_n = 0{,}10$ [mg VSS.mg N^{-1}]), a theoretical average value for X_n may be found from

$$\bar{X}_n = Y_n R_s \Delta TKN/[(1+b_n R_s).R_h] \qquad (3.6)$$

where

ΔTKN = Average nitrified TKN [mg $N.\ell^{-1}$]

i.e.

$$\Delta TKN = TKN_{IN} - TKN_{EFF} - N_s \qquad (3.7)$$

where

TKN_{IN} = Average influent TKN concentration [mg $N.\ell^{-1}$]

TKN_{EFF} = Average effluent TKN concentration [mg $N.\ell^{-1}$]

N_s = Steady state heterotrophic nutrient nitrogen requirement [mg $N.\ell^{-1}$]

and

$$N_s = \{f_n[Y_h(1+fb_hR_s)(1-f_{us}-P.f_{up})/(1+b_hR_s)] + f_{up}.f_n\}.S_{ti}$$

These equations formed the basis for determining the value of μ_{nmT}.

In this experimental series evaluation of μ_{nmT} was based on the response of a CMSR system under square wave flow and load (12h on, 12h off) subjected to anoxic conditions 2 hours after the beginning of the feeding period, for a period of 2 hours (experiment EST 32). The observed nitrate concentrations were plotted in Fig 3.4 and a smooth curve drawn through the data points. Values for $[NO_3]_{obs}$ were read off the smooth curve. Table 3.6 was then constructed by estimating the nitrification and denitrification rates, $r[NO_3]_r$ and $-r[NO_3]_r$, respectively from $r[NO_3]_{obs}$, and taking cognisance of the hydraulic rate, $r[NO_3]_h$, as described in Section 3.3.1. From Table 3.6, the average nitrification rate subsequent to the anoxic period, during which the ammonia concentration was above 2[mg N.ℓ^{-1}], can be calculated

$$\overline{r[NO_3]}_r = (5,4+5,9+5,8)/3 = 5,7 \text{ [mg N.}\ell^{-1}\text{.h}^{-1}\text{]}$$

From Eq (3.7),

$$\Delta TKN = TKN_{IN}-TKN_{EFF}-N_s = 49-6,5-11,3 = 31,2$$

From Eq (3.6),

$$\overline{X}_n = Y_nR_s\Delta TKN/[(1+b_nR_s).R_h] = 62 \text{ [mg VSS.}\ell^{-1}\text{]}$$

hence,

$$\mu_{nm14} = (\overline{r[NO_3]}_r.Y_n)/X_n$$

$$= 5,7.0,1.24/62 = 0,22[d^{-1}]$$

Accepting the temperature dependency equation, i.e.

$$\mu_{nmT} = \mu_{nm20}\ (1,123)^{T-20}$$

hence,

$$\mu_{nm20} = 0,44[d^{-1}].$$

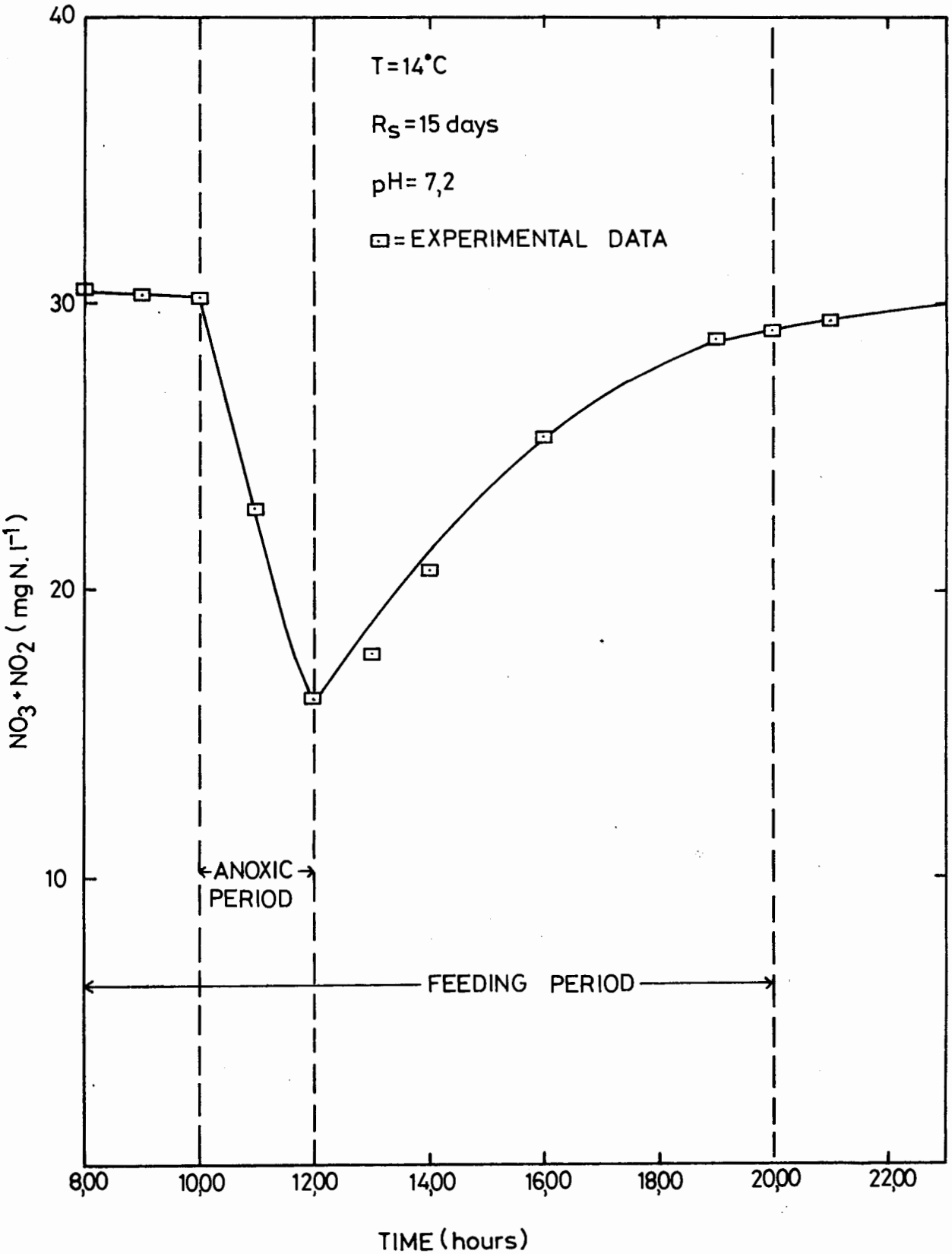

Fig.3.4: Smoothing of the observed nitrate data from experiment EST32.

Table 3.6 *Calculated nitrification and denitrification reaction rates from a smooth curve of the observed nitrate response.*

Time [h]	NO_3 [mg N.ℓ^{-1}]	Δt [h]	$r[NO_3]_{obs}$ [mg N.$\ell^{-1}h^{-1}$]	$r[NO_3]_h$ [mg N.$\ell^{-1}h^{-1}$]	$r[NO_3]_r$ [mg N.$\ell^{-1}h^{-1}$]
8,00*	30,3				
		1	0,0	5,07	5,1
9,00	30,3				
		1	0,0	5,07	5,1
10,00***	30,3				
		1	7,8	4,4	3,4
11,00	22,5				
		1	6,2	3,23	3,0
12,00****	16,3				
		1	2,5	2,93	5,4
13,00	18,8				
		1	2,6	3,35	5,9
14,00	21,4				
		2	1,95	3,89	5,8
16,00	25,3				
		3	1,1	4,5	5,6
19,00	28,6				
		1	0,5	4,81	5,3
20,00**	29,1				
		1	0,40	0,0	0,4
21,00	29,5				

* start feed period

** end feed period

*** start anoxic period

**** end anoxic period

3.3.2a(II) Estimation of f_{ca}

The easily biodegradable COD fraction of the influent, f_{ca}, was estimated from the precipitous drop in oxygen uptake rate at feed cessation as follows:

The total drop in oxygen uptake rate during feed cessation, ΔO_t is given by

$$\Delta O_t = \Delta O_{sbs} + \Delta O_n \qquad (3.8)$$

where

ΔO_n = Drop in oxygen uptake rate associated with termination of nitrogen available for nitrification entering with the feed [mg $O.\ell^{-1}.h^{-1}$].

ΔO_{sbs} = Drop in oxygen uptake rate associated with termination of easily biodegradable COD entering with the feed [mg $O.\ell^{-1}.h^{-1}$].

Theoretically f_{ca} is given by

$$f_{ca} = (\Delta O_{sbs}.R_a)/[(1-PY_h).S_{bi}] \qquad (3.9)$$

where

R_a = Actual influent hydraulic retention time during the feed period [h].

$S_{bi} = S_{ti}(1-f_{us}-P.f_{up})$ = Total biodegradable influent COD concentration on the day experiment was conducted [mg $COD.\ell^{-1}$]

From Table 3.5b the experimental values of the oxygen uptake rate (O.U.R) are plotted (in Fig 3.5) and a smooth curve is drawn through these points. The average O.U.R. before feed termination is 42,5 [mg $O.\ell^{-1}.h^{-1}$] and the average O.U.R. just after feed termination is 17,0 [mg $O.\ell^{-1}.h^{-1}$]. Hence the drop in O.U.R. is

ΔO_t = 42,5-17,0 = 25,5 [mg $O.\ell^{-1}.h^{-1}$].

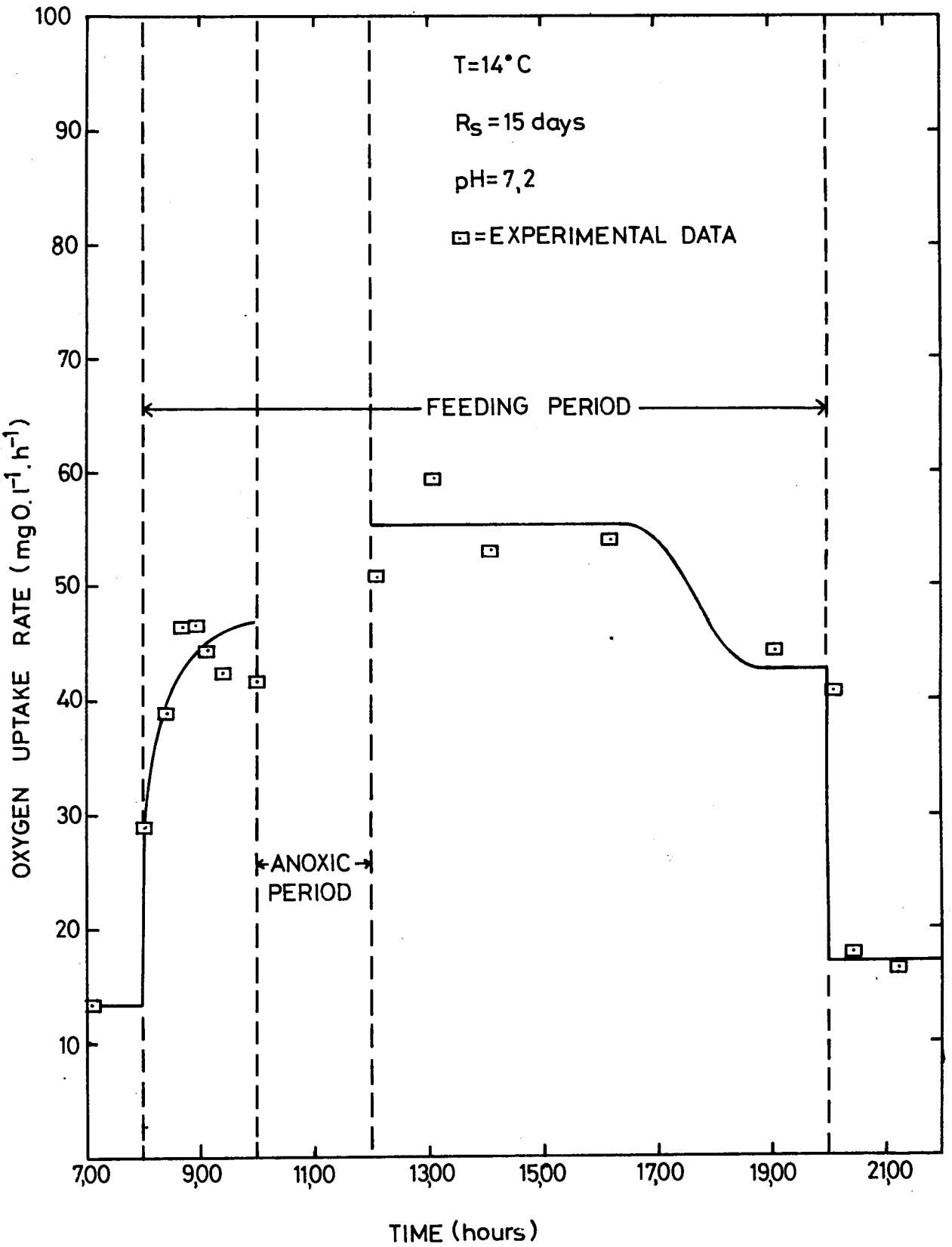

Fig. 3.5: Smoothing of the observed oxygen uptake rate data from experiment EST32.

From Section 3.3.2a(I) the average nitrification rate before feeding termination was estimated to be 5,6 [mg NO_3-N.ℓ^{-1}.h^{-1}], and just after feed termination, at 0,4 [mg NO_3-N.ℓ^{-1}.h^{-1}] (see Table 3.6). Hence the decrease in the nitrification reaction rate is 5,6-0,4 = 5,2 [mg N.ℓ^{-1}.h^{-1}] corresponding to a decrease in O.U.R. of

ΔO_n = 5,2.4,57 = 23,8 [mg O.ℓ^{-1}.h^{-1}].

From Eq (3.8), the drop in O.U.R. associated with the easily biodegradable COD is

$\Delta O_{sbs} = \Delta O_t - \Delta O_n$ = 25,5-23,8 = 1,7 [mg O.ℓ^{-1}.h^{-1}].

Substituting in Eq (3.9), i.e:

f_{ca} = (1,7.6)/[(1-1,54.0,45).493.(1-0,12-1,54.0,09)], yielding, f_{ca} = 0,09 [mg COD.mg COD^{-1}]. This value is designated the "indirect" estimation of f_{ca}.

A direct, and independent, estimation of f_{ca}, using a short sludge age completely mixed aerobic reactor, as described in Section 2.3.8, yields f_{ca} = 0,10 [mg COD.mg COD^{-1}].

Comparing the values of f_{ca} found by the two procedures above, the estimates differ slightly. The direct measure of f_{ca} (f_{ca} = 0,1) from experience is consistent and reproducible and hence can be considered reliable. The indirect method, in contrast, is heavily dependent on the stability of nitrification and oxygen uptake rates. From Table 3.5b it is apparent that in experiment EST 32 the value of O.U.R. before feed termination fluctuated in value up to 4,3 [mg O.ℓ^{-1}.h^{-1}] from the average. From Table 3.6 it is apparent that in experiment EST 32 the value of the nitrification rate before feed termination fluctuated in value up to 0,3 [mg N. $^{-1}$.h^{-1}] from the average, which is equivalent to 0,3.4,57 = 1,4 [mg O.ℓ^{-1}.h^{-1}]. The fluctuations in the nitrification rate values together with the large fluctuations in the O.U.R. values, lead to uncertainty in the estimation of ΔO_{sbs} at feed cessation which ultimately leads to an uncertain estimation of f_{ca}.

O_{sbp} = Oxygen uptake rate associated with utilization of slowly biodegradable COD [mg COD.ℓ^{-1}.h^{-1}]

K_{spT} = Half saturation value for slowly biodegradable COD [mg COD.mg VSS^{-1}]

Evaluation of K_{mpT} at a particular instance requires the evaluation of O_{sbp}, X_a and the Levenspiel ratio, i.e. $X_sP/(X_sP + X_a.K_{spT})$.

With the exception of O_{sbp} which can be determined from experimental observation with its associated experimental error, all the other parameters (X_a and the Levenspiel ratio) must be estimated, so that attention needs to be given to the errors induced in the estimation of K_{mpT} due to errors in the estimates of these parameters.

Determination of O_{sbp}

In the square wave loaded anoxic-aerobic alternating CMSR system the value of O_{sbp} can be found from the O.U.R. profile just after feed cessation. The O.U.R. in this region is due to two oxygen demand rates:

(1) Rate of utilization of slowly biodegradable particulate COD, S_{bp};

O.U.R. due to carbonaceous metabolism subsequent to feed termination, in terms of the death regeneration approach, is virtually solely due to the slowly biodegradable particulate COD, S_{bp}. The easily biodegradable soluble COD, S_{bs}, effectively terminates the moment the influent source of S_{bs} terminates.

(2) Rate of nitrification of ammonia derived from ammonification of TKN released by cell death and lysis;

at long sludge ages the nitrification rate is sufficiently high that immediately subsequent to feed termination the ammonia

derived from ammonia in the influent is effectively reduced to zero. The only remaining source of ammonia is that of ammonified TKN generated by death and lysis less ammonia needed for cell regeneration.

Comparing the relative magnitudes of these rates subsequent to feed termination, that due to S_{bp} is the overwhelmingly greater. From simulated response using the general model for 15 days sludge age at 14°C, the O.U.R. due to nitrification subsequent to feed termination is of the order of 2 to 4% of that due to S_{bp} and can be neglected for all practical purposes*. Consequently the O.U.R. subsequent to feed termination can be accepted to be wholly due to S_{bp} utilization.

Estimation of X_a

The value of X_a from dynamic steady state computer simulation (see Section 3.3.2b) of square wave conditions for experiment EST 32, with f_{ca} = 0,10 [mg COD.mg COD^{-1}], μ_{nm20} = 0,48[d^{-1}], K_{mp20} = 2,3 [mg COD.mg VSS^{-1}.d^{-1}] and η = 0,38 varies from about 1262 to 1310 [mg VSS.ℓ^{-1}] with an average of 1285 [mg VSS.ℓ^{-1}]. The steady state value of X_a under constant flow and load is given by inserting values into the following Eq. (3.11)

$$X_a = Y_h S_{bi} R_s / [(1+b_h R_s).R_h] \qquad (3.11)$$

Inserting the relevant S_{bi}, R_s and R_h values into Eq. (3.11), the steady state constant flow and load value of X_a for the *average* loading conditions of experiment EST 32 is

X_a = 0,45.375,9.15/[(1+0,202.15).0,5]

i.e.

X_a = 1259 [mg VSS.ℓ^{-1}]

the error involved in accepting a steady state constant flow and load X_a (1259[mg VSS.ℓ^{-1}]), against the peak X_a (1310[mg VSS.ℓ^{-1}]),

---

* The errors in the experimentally measured total O.U.R. are at least of the same order of magnitude as the O.U.R. due to nitrification subsequent to feed termination, hence, an attempt to correct for this nitrification is meaningless.

or the square wave average X_a (1285[mg VSS.ℓ^{-1}]), is small. Hence the steady state constant flow and load X_a is assumed in all further manual calculations.

Evaluation of the Levenspiel ratio and hence K_{mpT}.

It has been shown that O_{sbp} can be experimentally determined and that a steady state constant flow and load approximation for X_a can be accepted. It follows from Eq. (3.10) that the precision in the estimation of K_{mpT} depends to a large extent on the estimation of the Levenspiel ratio ($X_s.P/[X_s.P+X_a.K_{spT}]$) at the moment when K_{mpT} is evaluated, i.e. just prior to the instance of feed cessation in a square wave cycle, which in turn depends on the estimation of X_s just prior to the instance of feed cessation. From dynamic steady state computer simulations (see Section 3.3.2b), just before feed termination X_s is at its maximum value; unfortunately this peak X_s, X_{sp}, cannot be determined manually. Guide lines on the best procedure to evaluate K_{mpT} can be obtained from a simulation based investigation of the way the peak X_s and its corresponding Levenspiel ratio changes for an expected range of K_{mpT} values.

In Table 3.7 is listed a range of Levenspiel ratios corresponding to the widest range of K_{mpT} values encountered by Ekama and Marais (1978) and Van Haandel and Marais (1981), K_{mp20} = 2,2 to 3,0 [mg COD.mg $VSS^{-1}.d^{-1}$], for the operational conditions employed in experiment EST 32.

Table 3.7 *Possible variations of the Levenspiel ratio due to possible variations of peak X_s in experiment EST 32.*

K_{mp20} [mgCOD.mgVSS^{-1}.d^{-1}]	X_{sp} [mgVSS.ℓ^{-1}]	$X_{sp}.P/[X_{sp}.P+X_aK_{spT}]$
2,2	436	0,89
2,3	370	0,87
2,5	298	0,84
2,7	254	0,82
3,0	208	0,79

From Table 3.7, if an average Levenspiel ratio of 0,84 is accepted in estimating K_{mp20} for experiment EST 32, the maximum theoretical error in the estimation of K_{mp20} is 5 per cent, i.e. if estimates of the Levenspiel ratios under the specific operating conditions are possible (by means of a computer), good estimates for K_{mpT} can be calculated and the theoretical errors made in accepting these estimates can be determined.

In the absence of computer facilities the Levenspiel ratio can be assumed to be a unity, in which event Eq. (3.10) is reduced to

$$K_{mpT} = O_{sbp}/[(1-PY_h).X_a] \qquad (3.12)$$

This condition will be closely approximated if a high X_{sp} is ensured such that $X_{sp}.P >> X_a.K_{spT}$, in which event the estimation of K_{mpT} does *not* require knowledge of the magnitude of X_s.

One way of maintaining a high X_s is to have *repeated* anoxic intervals (e.g. 2 hours anoxic period followed by 4 hours aerobic period), instead of the single 2h anoxic period employed in this experiment. If X_s is maintained high by imposing the appropriate conditions, manual estimation of K_{mpT} is possible and the reliability of its magnitude is subject only to experimental errors related to the O.U.R: measurement. The experimental design in this investigation therefore was inadequate to determine K_{mpT} reliably without the aid of computer simulations.

3.3.2a(IV) Estimation of η

The ratio of slowly biodegradable utilization rate in an anoxic environment to that in an aerobic environment, $\eta = K'_{mpT}/K_{mpT}$ can be determined as follows:

$$\eta = \frac{\Delta N_{sbp}.2,86}{(1-PY_h).X_a.K_{mpT}} \qquad (3.13)$$

where

ΔN_{sbp} = Nitrate removal associated with the utilization of slowly biodegradable COD.

The magnitude of ΔN_{sbp} is given by

$$\Delta N_{sbp} = \Delta N - \Delta N_{sbs} \qquad (3.14)$$

where

ΔN = Total daily nitrate removal [mg N.d^{-1}]

ΔN_{sbs} = Daily nitrate removal due to the utilization of the easily biodegradable material [mg N.d^{-1}]

Assuming complete utilization of the easily biodegradable material, ΔN_{sbs} is given by

$$\Delta N_{sbs} = Q_a . t_a . S_{bi} . f_{ca} . (1-PY_h)/2,86 \qquad (3.15)$$

where

Q_a = Actual influent volumetric flow rate during the loading period [ℓ.h^{-1}]

t_a = Duration of the anoxic period [h]

S_{bi} = Total biodegradable influent COD concentration on the day testing was conducted [mg COD.ℓ$^{-1}$]

The certainty in the estimation of η depends primarily on the certainty with which K_{mpT} is estimated. This uncertainty is further increased by (1) any inaccuracies in the nitrate measurements during the anoxic period and (2) an inaccurate estimation of f_{ca}.

In this investigation the determination of K_{mpT} required computer simulations hence the determination of η also was not possible without this aid.

3.3.2b Determination of the values of all the nitrification and denitrification constants from an AAACMSR system under cyclic square wave flow and load feeding pattern by computer simulation

The dynamic steady state program developed by Dold, Ekama and Marais (1980) extended to include nitrification-denitrification systems by Van Haandel and Marais (1981) had to be modified so that it could be applied in determining the nitrification and denitrification kinetic constants from a cyclically square wave loaded AAACMSR system. The dynamic steady state (cyclic) program calculates the response of the plant over one daily cycle assuming the imposed cycle of flow and load

remains the same from day to day. The modification made was an extension of the program to accommodate a greater variety of operating conditions, by removing the restriction that a reactor in the process either is continuously aerated or continuously unaerated.

The general cyclic program now accommodates alternating unaerated-aerated periods in the daily cycle for each reactor, provided that, either the unaerated-aerated pair of time intervals add up to 24 hours or the unaerated-aerated pairs of intervals are a multiple of 24 hours.

The solution is found by numerical integration of the governing equations by an iterative procedure that continues until the solutions between two successive cycles differ by less than a preselected quantity for each of the parameters solved, (Van Haandel and Marais 1981). The starting values for the iterative procedure are found from the solution of a single reactor system under constant flow and load chosen such that the total flow and mass load per day are the same as under the cyclic flow and load conditions. The simulated daily cyclic response depends on the values assigned to the kinetic constants in the governing differential equations and the cyclic flow and load patterns.

The general dynamic steady state solution has been extensively used to determine the various constants in the governing equations. This is done by curve fitting; the constants are progressively changed until the best fit between observation and prediction is obtained. The difficulty with this approach is that depending on the sludge age, some of the responses become insensitive to the value selected for some constants. To obtain reliable solution of the constants it is necessary therefore to perform the tests over a range of sludge ages using the same sewage. To determine a particular constant, a transient in the response needs to be created that is governed in a large measure by the constant for which an accurate evaluation is sought.

The magnitude of a transient usually is affected by (1) the sludge age, (2) the cyclic pattern of the influent flow and/or load and/or (3) a change in the operating condition at some point in the cycle.

For the purpose of estimating μ_{nmT}, K_{mpT}, η and f_{ca} the following conditions were imposed in order to obtain the most reliable results:

(1) To obtain maximum activity in the sludge the shortest practical sludge age that allows continuous and stable nitrification was sought; this was found to be about 15 days. (For one particular batch of sewage, when operating at R_s = 10 days, nitrification declined consistently even with repeated re-innoculation of nitrifying sludge).

(2) A square wave cyclic flow and load input was selected (12 hours on 12 hours off) because at the time it was thought that the transients created at the end of the feeding period would allow the fraction of easily biodegradable COD, f_{ca}, to be determined in addition to the nitrification and denitrification kinetic constants.

(3) A qualitative change in the operating conditions was imposed by interrupting the air supply every day for a period of two hours. The transient thus created was predicted to give rise to large changes in ammonia, nitrate and alkalinity thereby allowing reliable estimates of μ_{nmT}, K_{mpT} and η.

An alternating anoxic-aerobic CMSR system in an apparent dynamic steady state was operated as described earlier in Section 3.3.2. By choosing a two hour anoxic period during the high flow period, the parameters affected most significantly during the anoxic period and on subsequent aeration are NH_3, TKN, NO_3 and Alk. The absolute magnitudes of the changes expected (and observed) are high and therefore should allow a reliable determination of the constants by curve fitting.

The solution procedure for determining the nitrification and denitrification constants using the dynamic steady state program is based on trial and error curve fitting. The required input data to the dynamic steady state program is:

(1) Operational conditions
(2) Cyclic loads
(3) Sewage characteristics

(4) Kinetic constants and their temperature dependence.

(1) The operational conditions for the AAACMSR under consideration, depicted in Fig. 3.3, are listed in Table 3.4.

(2) The cyclic loads are ideally identical. However due to experimental difficulties in maintaining an identical load for each cycle, the input load fluctuates from cycle to cycle. In Table 3.4 is given the fluctuations of cyclic COD and TKN mass inputs. In addition the *average* load, disregarding any outliers, for all the cycles is indicated. This average value is the value used in the dynamic steady state program simulations.

(3) All sewage characteristics are listed in Table 3.4. With regard to f_{ca}, it has been shown in Section 3.3.2a(II) that the estimated value of f_{ca} from a square wave loaded AAACMSR is of the same order of magnitude as the error made in the measurement, hence any value of f_{ca} determined by curve fitting has little or no reliability. Consequently, the value of f_{ca}, given in Table 3.4, was found from a short sludge age single aerobic reactor experiment, specifically devised for this purpose, as described in Section 2.3.8.

(4) All kinetic constants and their temperature dependence, other than those for which evaluation is sought, i.e. μ_{nmT}, K_{mpT} and η, were identical to those used by Van Haandel and Marais (1981). Preliminary estimates of μ_{nmT}, K_{mpT} and η were given by their manually determined values, and for cases where K_{mpT} and η could not be determined reliably by manual means, because of unproductive operating conditions, an accepted average value was used (see Section 3.3.2a).

Dynamic steady state simulations were carried out for experiment EST 32 and each of μ_{nmT}, K_{mpT} and η, respectively, was changed in turn, while keeping all the other constants at their preliminary estimates until the closest fit with experimentally observed response was obtained. By computer trial and error simulations for closest fit of experiment EST 32, using the general dynamic steady state program (program listing is given in Appendix A.1),

and with f_{ca} = 0,10, *average* influent TKN = 49 [mg $N.\ell^{-1}$], *average* influent COD = 507 [mg $COD.\ell^{-1}$], *average* sewage characteristics given in Table 3.4 and *actual measured* alkalinity = 412 [mg $CaCO_3.\ell^{-1}$] (given in Table 3.5b), the following constants were evaluated: K_{mp20} = 2,3 [mg COD.mg $VSS^{-1}.d^{-1}$], η = 0,38, μ_{nm20} = 0,48 [d^{-1}]. A very good correlation between the experimental and simulated responses of experiment EST 32 is given in Fig. 3.6b.

Using the constants above, the response was simulated for experiment EST 31 with f_{ca} = 0,10 [mg COD.mg COD^{-1}], *average* influent TKN = 49 [mg $N.\ell^{-1}$], *average* influent COD = 507 [mg $COD.\ell^{-1}$], *average* sewage characteristics given in Table 3.4 and *actual measured* alkalinity = 413 [mg $CaCO_3.\ell^{-1}$] (given in Table 3.5a). The same batch of sewage used in experiment EST 32 was also used in experiment EST 31; the difference between experiment EST 32 and EST 31 is that the anoxic period was introduced 2 and 1 hours, respectively, after the beginning of the feed period. The observed and simulated responses for experiment EST 31 are shown in Fig. 3.6a. These show close correlation, indicating that the square wave loaded AAACMSR system is a reliable method for the determination of the nitrification and denitrification constants.

The value of μ_{nm20} for the batch of sewage used in experiments (EST 31 and EST 32) was manually estimated in Section 3.3.2a(I) to be 0,44 [d^{-1}]. Utilizing μ_{nm20} = 0,48 [d^{-1}] in the dynamic steady state computer program simulations for experiments (EST 31 and EST 32) gave close correlation between observed and simulated responses [Figs. 3.6 (a and b)]. This proves the method for the manual estimation of μ_{nmT} to be reliable and reasonably accurate.

3.3.3 Alternating anoxic-aerobic CMSR (AAACMSR) system under constant flow and load

Van Haandel and Marais (1981) investigated an AAACMSR system under constant flow and load at 20°C and found that the response indicated very good stability, and allowed an accurate evaluation of the nitrification and denitrification constants - provided the fraction of easily biodegradable influent COD, f_{ca} was known. To determine the fraction of easily biodegradable COD, f_{ca}, a separate special experimental set up and investigation was required, described in Section 2.3.8.

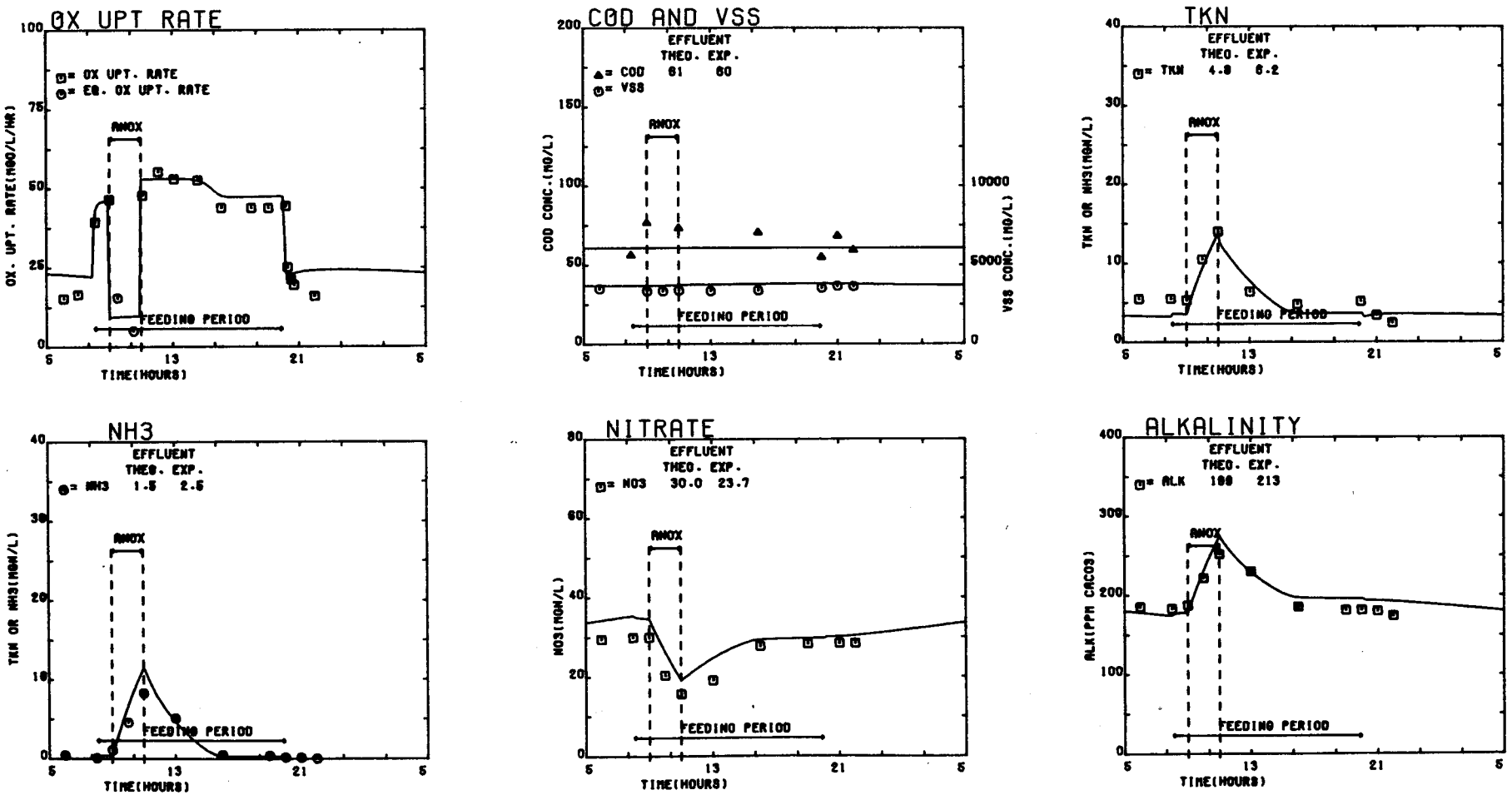

Fig.3.6a: Closest fit of the observed response of an AAACMSRS under square wave flow and load using the dynamic steady state program at 14°C, R_s = 15 days, pH= 7,2, with a single anoxic period of 2 hours in 24, introduced 1 hour after the beginning of the feeding period (Experiment EST 31).

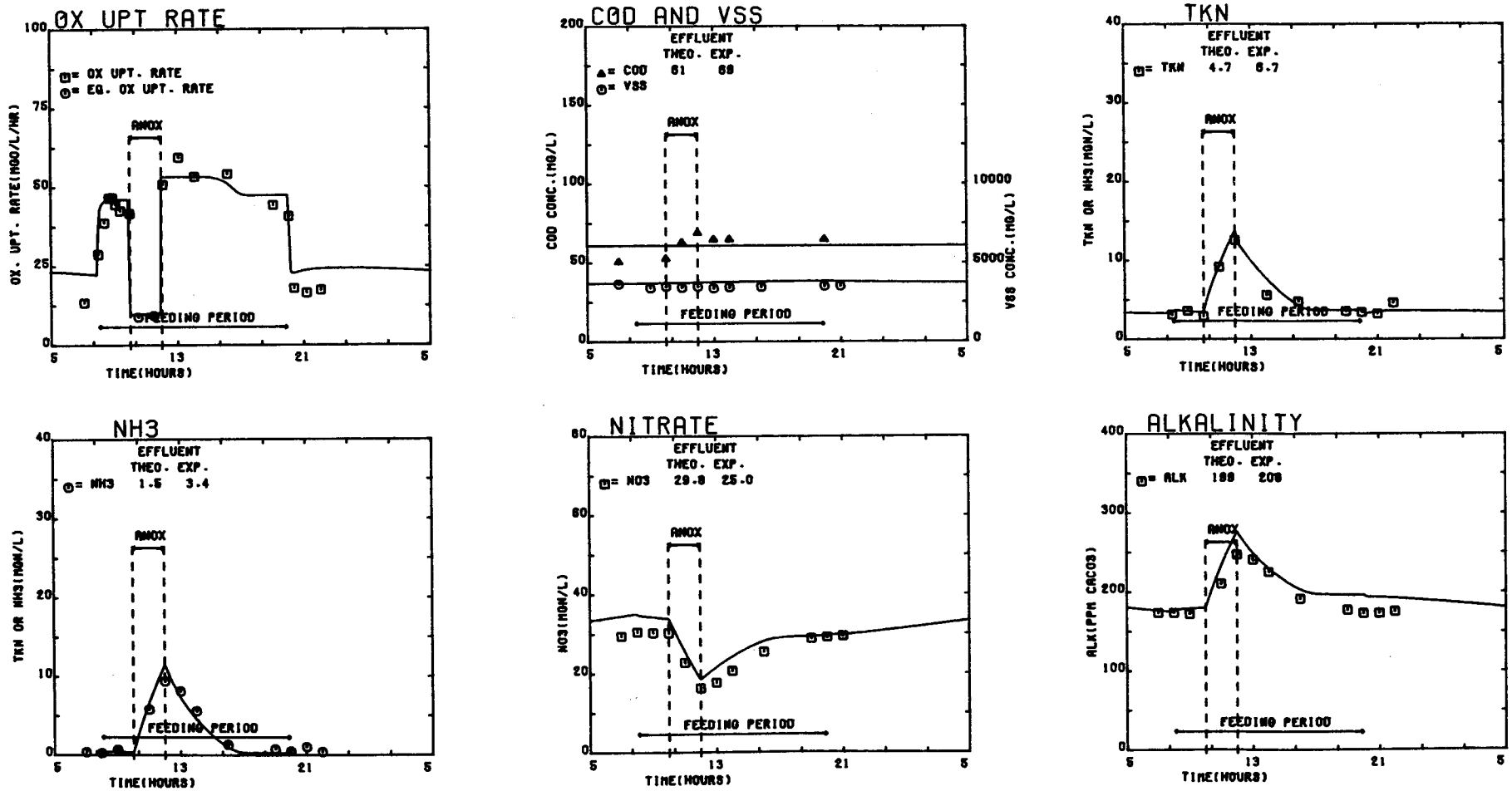

Fig.3.6b: Closest fit of the observed response of an AAACMSRS under square wave flow and load using the dynamic steady state program at 14°C, R_s = 15 days, pH=7,2, with a single anoxic period of 2 hours in 24, introduced 2 hours after the beginning of the feeding period (Experiment EST 32).

The alternating anoxic-aerobic CMSR system under constant flow and load has been adopted only very recently (1980) for the purpose of evaluating the nitrification and denitrification constants, and then only at 20°C. No experiments at other temperatures have been undertaken. Consequently to check the value of the method at lower temperatures, experiments were carried out at 14°C under steady state constant flow and load.

The experimental set up is shown in Fig. 3.3 and details of operational and sewage characteristics are listed in Table 3.8. Sequential aerobic and anoxic conditions were induced by switching the electrical current, to an air pump, on and off. The system was run for 2 weeks before intensive testing was undertaken, so that stable conditions could develop. During this period the VSS and mean effluent TKN were checked daily; it was presumed that when these showed no change, steady state had been achieved.

Once steady state had been achieved, intensive testing was done over that fraction of anoxic-aerobic period during which rapid changes of concentrations of nitrate, alkalinity, TKN and NH_3 took place. Samples were taken every hour and the following process variables monitored: Oxygen uptake rate, COD, VSS, TKN, NH_3, NO_3 and Alk. Three such experiments were carried out in this fashion at approximately one week intervals.

The first two experiments (EST 11 and EST 12) were carried out in an *identical* manner (3 hour anoxic period followed by 21 hour aerobic period) on the *same* batch of sewage. The responses are listed in Tables 3.9(a and b), respectively. In order to determine the easily biodegradable COD fraction, f_{ca}, a short sludge age completely mixed aerobic reactor was run under cyclic square wave flow and f_{ca} determined in accordance with the procedure described in Section 2.3.8. The value of f_{ca} was found to be 0,10 [mg COD. mg COD^{-1}]. From data obtained in experiment EST 11, the nitrification *reaction* rates were calculated from the *observed* nitrate profile for every hour interval using the procedure as described in Section 3.3.1. Evaluation of μ_{nm20} from these rates is described earlier in Section 3.3.2a(I) and was found to be 0,31 [d^{-1}]. By computer trial and error simulations for closest fit, using the general dynamic

Table 3.8 *Operational and average sewage characteristics used in Fig. 3.3 under constant flow and load with a single anoxic period of 3 hours in 24.*

Operational Characteristics

T = 14°C Reactor volume, V = 15 [ℓ]

R_s = 15 [d] Hydraulic retention time, R_h = 12 [h]

Duration of stable* operation before testing commenced = 14 [d]

Sewage Characteristics

		Average**
Influent COD	= 444 to 520 [mg COD.ℓ^{-1}]	486 [mg COD.ℓ^{-1}]
Influent TKN	= 48,9 to 59,9 [mg N.ℓ^{-1}]	54 [mg N.ℓ^{-1}]

f_{ca} = 0,10 [mg COD.mg COD^{-1}] (determined experimentally as described in Section 2.3.8)

f_{up} = 0,09 [mg VSS.mg COD^{-1}]

f_{us} = 0,15 [mg COD.mg COD^{-1}]

f_{na} = 0,75 [mg NH_3-N.mg N^{-1}]

f_{nu} = 0,0 [mg N.mg N^{-1}]

* Stable operation characteristic to steady state conditions refers to constant VSS and consistent nitrification with a corresponding constant mean effluent ammonia.

** Disregarding any outliers.

Table 3.9a *Observed response of a CMSR system under constant flow and load conditions (experiment EST 11) at 14°C, R_s = 15 days, pH = 7,25*

SAMPLE	TIME [h]	NH_3 [mgN.ℓ^{-1}]	TKN [mgN.ℓ^{-1}]	NO_3 [mgN.ℓ^{-1}]	ALKALINITY [mg$CaCO_3$.ℓ^{-1}]	COD [mgCOD.ℓ^{-1}]	VSS [mgVSS.ℓ^{-1}]	TIME [h]	O.U.R. [mgO.ℓ^{-1}.h^{-1}]
Influent	-	34,35	53,6	0,0	439,0	515,1	-	-	-
Effluent	-	2,48	4,0	35,0	187,0	75,8	-	-	-
1	15,00	0,17	1,3	36,6	169,0	-	-	15,12	25,0
2	16,00	0,27	2,1	36,2	166,0	71,7	3566,0	16,08	29,2
3	17,00*	0,35	1,6	36,4	162,0	-	-	16,75	27,6
4	18,00	2,90	6,1	32,3	193,0	75,8	3540,0	-	-
5	19,00	5,77	9,0	26,8	217,0	-	-	-	-
6	20,00**	7,73	9,3	21,9	242,0	79,9	3564,0	20,18	42,4
7	21,00	6,18	8,5	25,3	230,0	-	-	21,07	43,5
8	22,00	4,36	7,2	28,1	214,0	79,9	3586,0	22,10	43,2
9	23,00	2,93	5,2	30,5	198,0	-	-	23,17	45,0
10	24,00	0,57	2,8	33,2	178,0	63,5	3621,0	24,13	38,5

* begin anoxic period

** end anoxic period

Table 3.9b *Observed response of a CMSR system under constant flow and load conditions (experiment EST 12) at 14°C, R_s = 15 days, pH = 7,2*

SAMPLE	TIME [h]	NH_3 [mgN.ℓ^{-1}]	TKN [mgN.ℓ^{-1}]	NO_3 [mgN.ℓ^{-1}]	ALKALINITY [mg$CaCO_3$.ℓ^{-1}]	COD [mgCOD.ℓ^{-1}]	VSS [mgVSS.ℓ^{-1}]	TIME [h]	O.U.R. [mgO.ℓ^{-1}.h^{-1}]
Influent		43,4	54,9	0,0	427,0	524,3	-	-	-
Effluent		2,35	4,6	35,1	183,0	67,2	-	-	-
1	15,00	0,70	2,5	36,6	166,0	-	-	15,28	31,7
2	16,00	0,22	-	37,9	163,0	75,8	3734,0	16,33	31,4
3	17,00*	-	3,1	37,9	-	-	-	16,82	30,6
4	18,00	3,53	7,3	33,7	190,0	75,8	3720,0	-	-
5	19,00	6,48	10,3	28,0	218,0	-	-	-	-
6	20,00**	9,02	11,0	23,1	238,0	73,7	3684,0	20,10	45,0
7	21,00	7,82	10,3	25,3	229,0	-	-	21,10	47,5
8	22,00	5,75	8,2	27,6	216,0	69,6	3731,0	22,17	45,2
9	23,00	2,57	5,1	32,3	191,0	-	-	23,10	45,3
10	24,00	0,32	3,6	34,8	171,0	71,7	3631,0	24,08	35,0
11	1,00	0,27	2,8	35,1	168,0	-	-	1,13	32,3
12	2,00	0,19	3,3	35,9	167,0	-	-	2,05	30,8

* begin anoxic period

** end anoxic period

steady state program, and with f_{ca} = 0,10, *average* influent COD = 486,0 [mg COD.ℓ^{-1}], *average* influent TKN = 54,0 [mg N.ℓ^{-1}], *average* sewage characteristics given in Table 3.8 and *actual measured* alkalinity = 439,0 [mg $CaCO_3$.ℓ^{-1}] (given in Table 3.9a), the following constants were evaluated: K_{mp20} = 2,3 [mg COD.mg VSS^{-1}.d^{-1}], η = 0,38, μ_{nm20} = 0,33 [d^{-1}]. Excellent correlation was observed between the experimental and simulated responses[see Fig 3.7a] so that it is very likely that the constants found above were reliable.

Using the constants derived above, the response was simulated for the second experiment (EST 12), using the general dynamic steady state program with f_{ca} = 0,10, *average* influent COD = 486,0 [mg COD.ℓ^{-1}], *average* influent TKN = 54,0 [mg N.ℓ^{-1}], *average* sewage characteristics given in Table 3.8 and *actual measured* alkalinity = 427,0 [mg $CaCO_3$.ℓ^{-1}] (given in Table 3.9b). The observed and simulated responses are shown in Fig. 3.7b. These show close correlation, indicating that the experimental procedure gave rise to remarkably reproducible data; this verifies the findings of Van Haandel and Marais (1981) that the constant flow and load AAACMSR system is a reliable method for the determination of the nitrification and denitrification constants.

In the two experiments the observed and simulated responses showed very good correlation for oxygen uptake rate, COD, VSS, TKN, ammonia (NH_3), nitrate (NO_3) and alkalinity (Alk), [Figs. 3.7(a and b)], and lend support to the adequacy of the general dynamic steady state model under time varying input conditions. In particular it verifies the reliability of the alkalinity parameter, recently incorporated into the general model, as an additional check on the nitrification and denitrification behaviour of a single sludge system.

To investigate the effect of the length of anoxic period on the *nitrification* response, a third experiment (EST 21) was carried out with a relatively long anoxic period i.e. 4 hour anoxic period (instead of 2 hour) followed by a 20 hour aerobic period. It was hypothesized that if the anoxic period affects the nitrifiers, the nitrification rate may show a decline for a certain period of time immediately after aerobic conditions are reimposed. By computer trial and error simulations for closest fit of experiment EST 21,

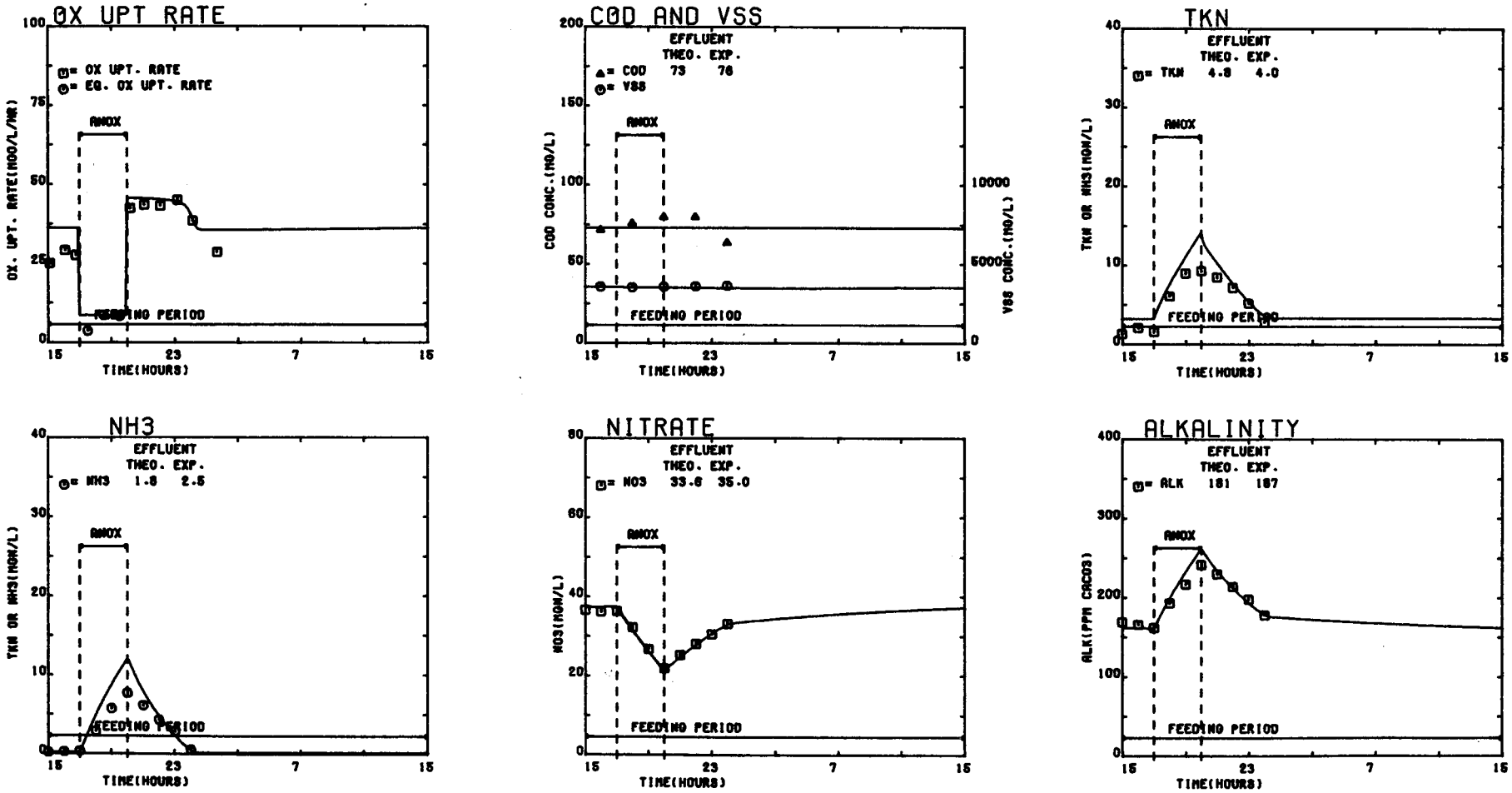

Fig.3.7a: Closest fit of the observed response of an alternating anoxic-aerobic completely mixed single reactor system (AAACMSRS) under constant flow and load using the dynamic steady state program at 14°C, R_s = 15 days, pH=7,25, f_{ca}=0,10[mgCOD.mgCOD^{-1}], with a single anoxic period of 3 hours in 24 (Experiment EST 11).

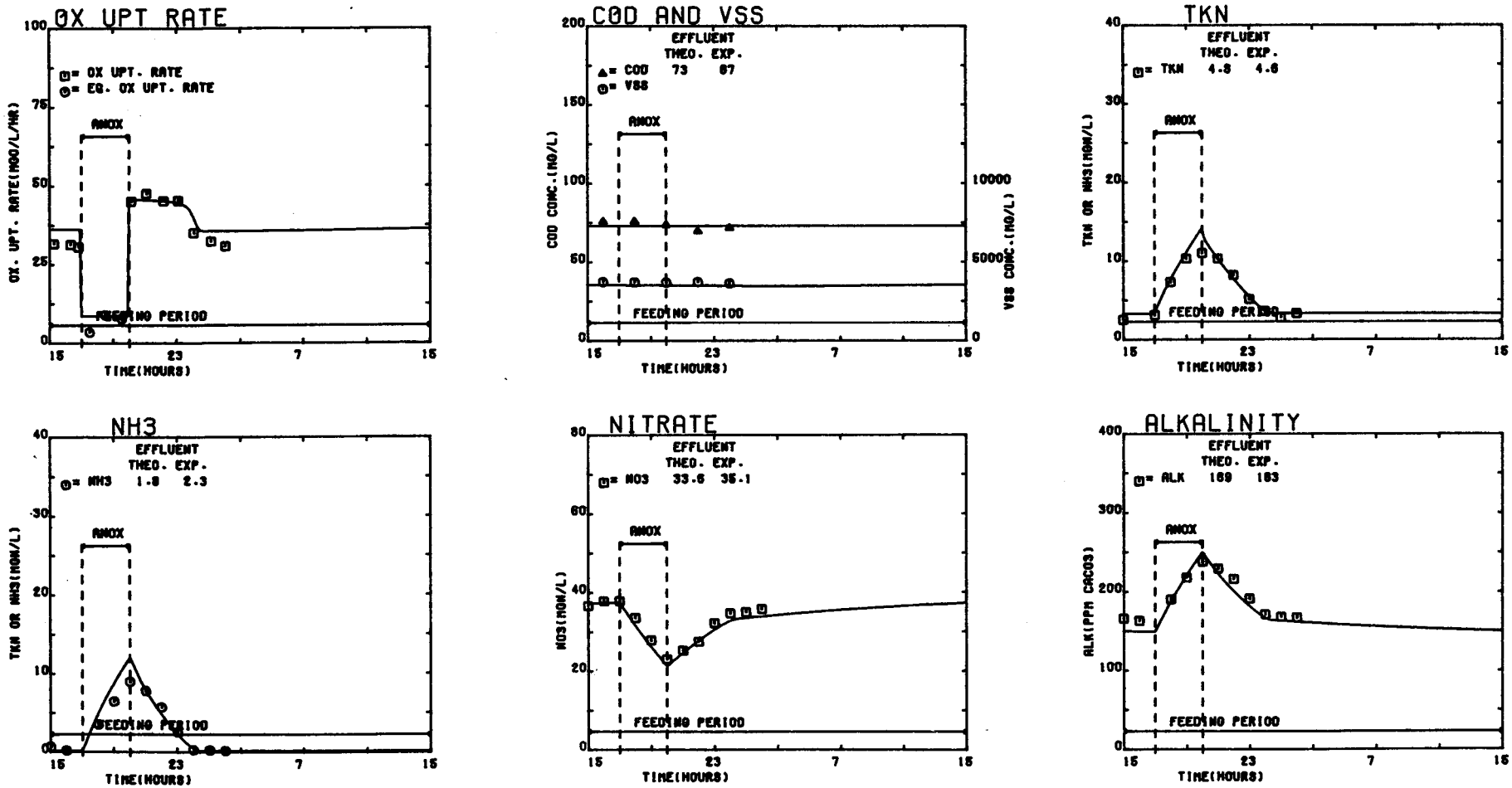

Fig.3.7b: Closest fit of the observed response of an AAACMSRS under constant flow and load using the dynamic steady state program at 14°C, R_s = 15 days, f_{ca}=0,10 [mgCOD.mgCOD^{-1}], pH=7,2, with a single anoxic period of 3 hours in 24 (Experiment EST 12).

using the general dynamic steady state program and with f_{ca} = 0,10 [mg COD.mg COD^{-1}], *average* influent COD = 489,0 [mg COD.ℓ^{-1}], *average* influent TKN = 46,0 [mg N.ℓ^{-1}], *average* sewage characteristics given in Table 3.10 and *actual measured* alkalinity = 401,7 [mg $CaCO_3$.ℓ^{-1}] (given in Table 3.11), the following constants were evaluated: K_{mp20} = 3,0 [mg COD.mg VSS^{-1}.d^{-1}], η = 0,38, μ_{nm20} = 0,33 [d^{-1}]. A consistent* correlation between the experimental and simulated response of experiment EST 21 over *the whole* period monitored (Fig.3.8a) indicates unequivocably that the μ_{nmT} observed did not show evidence of change in the period immediately after termination of the anoxic period. If it did, it would not have been possible to consistently* fit the nitrate response curve by simulation during this period with a constant value for μ_{nmT}. Thus, for an anoxic period of 4 hours every 24 hours, the system nitrification appeared to be unaffected. This observation does not imply that such inhibition might not occur in other tests with different sources of sewage and different operational conditions.

Attention is now given to Fig. 3.8a where closest fit of experiment EST 21 does not satisfactorily describe the nitrate and alkalinity responses. Fig. 3.8a clearly indicates that when the *average* influent TKN load is used as an input data to the dynamic steady state program *for experiment EST 21*, the nitrate and alkalinity responses over the *whole* period monitored are *consistently* overestimated. In all other cases where the *average* influent TKN load was used as an input data to the dynamic steady state program, Figs. [3.6(a and b), and 3.7(a and b)], very good correlations between experimental and observed responses were obtained.

It is hypothesized that the failure of the dynamic *steady state* model to adequately describe the nitrate and alkalinity responses (i.e. the nitrification behaviour) in experiment EST 21 stems from *unsteady* operating conditions that prevailed on the day testing was conducted. Table 3.12 gives a comparative study of the deviation

*Although correlation of say the nitrate response in Fig. 3.8a is not excellent, it is *consistently* over predicted. It will be shown later that this problem arises due to limitations of the dynamic steady state model to describe the response governed by the experimental conditions employed in experiment EST 21, and it can be resolved without affecting the value of any of the kinetic constants.

Table 3.10 *Operational and average sewage characteristics used in Fig. 3.3 under constant flow and load with a single anoxic period of 4 hours in 24.*

Operational Characteristics

T = 14,7°C — Reactor volume, V = 15 [ℓ]

R_s = 15 [d] — Hydraulic retention time, R_h = 12 [h]

Duration of stable* operation before testing commenced = 5 [d]

Sewage Characteristics

		Average**
Influent COD	461,7 to 561,5 [mg COD.ℓ^{-1}]	489,0 [mg COD.ℓ^{-1}]
Influent TKN	45,4 to 53,1 [mg N.ℓ^{-1}]	46,0 [mg N.ℓ^{-1}]

f_{ca} = 0,10 [mg COD.mg COD^{-1}]

f_{up} = 0,09 [mg VSS.mg COD^{-1}]

f_{us} = 0,15 [mg COD.mg COD^{-1}]

f_{na} = 0,60 [mg NH_3-N.mg N^{-1}]

f_{nu} = 0,0 [mg N.mg N^{-1}]

* Stable operation characteristic to steady state conditions refers to constant VSS and consistent nitrification with a corresponding constant mean effluent ammonia.

** Disregarding any outliers.

Table 3.11 *Observed response of a CMSR system under constant flow and load conditions (experiment EST 21) at 14,7°C, R_s = 15 days, pH = 7,2*

SAMPLE	TIME [h]	NH_3 [mgN.ℓ$^{-1}$]	TKN [mgN.ℓ$^{-1}$]	NO_3 [mgN.ℓ$^{-1}$]	ALKALINITY [mg$CaCO_3$.ℓ$^{-1}$]	COD [mgCOD.ℓ$^{-1}$]	VSS [mgVSS.ℓ$^{-1}$]	TIME [h]	O.U.R. [mgO.ℓ$^{-1}$.h^{-1}]
Influent		33,28	52,9	0,0	401,7	561,5	-	-	-
Effluent		2,1	6,0	21,0	211,7	79,6	-	-	-
1	14,00	0,32	4,0	24,3	185,7	-	-	14,42	33,7
2	15,00	0,04	5,2	24,7	180,8	59,5	3788,0	15,15	33,3
3	16,00*	0,15	5,4	26,1	176,4	-	-	15,88	33,9
4	17,00	2,84	8,8	20,0	197,5	-	-	-	-
5	18,00	4,95	11,6	14,4	237,9	-	-	-	-
6	19,00	7,40	12,8	8,6	263,2	-	-	-	-
7	20,00**	9,04	17,5	2,6	283,8	109,9	3744,0	20,17	51,7
8	21,00	6,59	12,4	7,6	263,2	-	-	21,27	59,0
9	22,00	0,0	7,5	13,1	233,0	67,5	3749,0	22,15	44,8
10	23,00	0,11	5,8	17,7	206,5	-	-	23,02	36,0
11	24,00	0,0	5,4	19,2	203,4	65,5	3762,0	24,22	33,7
12	1,00	0,04	4,6	20,2	196,7	-	-	-	-
13	2,00	0,04	4,6	21,3	197,2	65,5	3743,0	2,75	33,0

* begin anoxic period

** end anoxic period

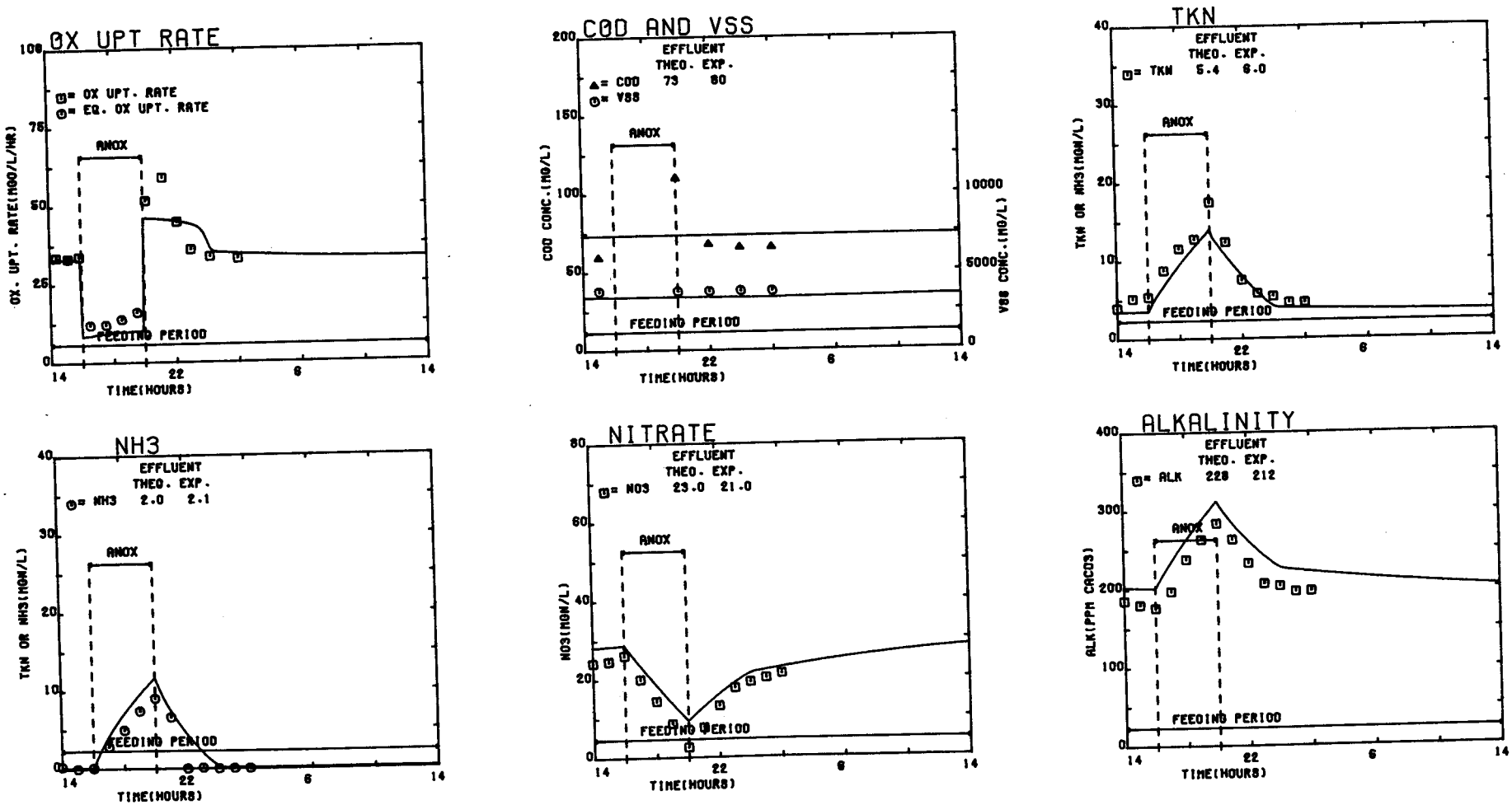

Fig.3.8a Closest fit of the observed response of an AAACMSRS under constant flow and load using the dynamic steady state program at 14,7°C, R_s = 15 days, f_{ca}=0,10 [mgCOD.mgCOD^{-1}], pH=7,2, with a single anoxic period of 4 hours in 24 (Experiment EST 21).

of nitrification behaviour in AAACMSR systems from dynamic steady state by comparing for all the AAACMSR experiments,

(1) the *average* influent TKN concentration used in the dynamic steady state simulations to the *actual measured* TKN concentration on the day testing was conducted, and

(2) the correlations obtained between experimental and observed nitrate and alkalinity responses.

Table 3.12 indicates that there exists a very strong correlation between the extent of deviation of *actual measured* influent TKN from the *average* influent TKN to the goodness of fit of nitrate and alkalinity responses; as the deviation from average influent TKN load decreases so the *actual dynamic steady state* nitrification behaviour is more closely predicted by the general *dynamic steady state program*, with concomitant closer correlations between the observed and predicted responses of nitrate and alkalinity. In principle the same reasoning can also be applied to the extent of deviation of the *actual measured* from the *average* influent COD but in practice, unless the magnitude of this deviation is large, the measurable parameters governed by COD utilization are either insensitive to the deviation or can not be directly used; the VSS test is insensitive to small deviations from dynamic steady state carbonaceous metabolic activities while the total oxygen uptake rate test includes dynamic steady state oxygen requirements for nitrification, which makes the estimation of dynamic steady state *carbonaceous* oxygen requirements heavily dependent on the validity of the nitrification description.

From the above discussion it seems that the dynamic steady state model is suitable for accurate estimations of the kinetic constants governing nitrification and denitrification from an AAACMSR system *only if* the operating conditions are such that the deviation from (average) dynamic steady state behaviour is small. Fortuitously this was the case in experiments (EST 31, EST 32, EST 11 and EST 12) each of which was operated under stable conditions for a period of 2 weeks or more before testing commenced. In experiment EST 21 however stable operation was maintained for 5 days only before testing commenced and the *actual measured* influent TKN load on the day testing

Table 3.12 *Comparative study of deviation of nitrification behaviour in AAACMSR systems from dynamic steady state.*

Experiment number	Stable Operation * [d]	Average ** influent TKN [mgN.ℓ$^{-1}$]	Actual *** measured influent TKN [mgN.ℓ$^{-1}$]	Deviation of average from actual measured influent TKN	Dynamic steady state closest fit Fig.number	Correlation between experimental and observed nitrate and alkalinity responses
EST 31	14	49,0	51,9	5,9%	3.6a	Satisfactory
EST 32	14	49,0	51,2	4,5%	3.6b	Satisfactory
EST 11	14	54,0	53,6	0,7%	3.7a	Excellent
EST 12	14	54,0	54,9	1,7%	3.7b	Very good
EST 21	5	46,0	52,9	15 %	3.8a	Unsatisfactory

* Stable operation is the period before testing commenced during which constant VSS and effluent ammonia were measured.

** Average influent TKN concentration disregarding any outliers.

*** Actual measured influent TKN on the day testing was conducted.

was conducted deviated by 15% from the *average* influent TKN load. This, *inter alia*, led to unsatisfactory description of the nitrification behaviour when using the dynamic steady state model, hence unsatisfactory predictions of nitrate and alkalinity responses were obtained [Fig. 3.8a].

Resolution of this problem necessitated a model that can accommodate deviations from ideal dynamic steady state (cyclicity). Such a flexible program is the unsteady state (transient) program developed by Van Haandel and Marais (1981). The application of the unsteady state program to determine the nitrification and denitrification constants from an alternating anoxic-aerobic CMSR system is as follows:

In simulations using the unsteady state program of Van Haandel and Marais (1981) the response is calculated by a non iterative straightforward integration procedure. In the unsteady state program the starting values of the process variables at the beginning of the experiment must be fed in as input data; the starting values of the measurable soluble parameters (S_u, NH_3, NON, NO_3, Alk) are obtained from experimental measurements while the variables that cannot be measured (X_a, X_s, X_e, X_i, S_{bp}, X_n) are estimated from theory, (e.g. by using the general dynamic steady state program).

In experiment EST 21 the *dynamic steady state* values of the sludge parameters, i.e. X_a, X_s, X_e, X_i, S_{bp} and X_n can be accepted. This is valid because the fluctuations in loads and sewage characteristics affect the values of the sludge parameters to a much lesser extent than the values of the soluble parameters; the sludge age is 15 days and this means that if approximate dynamic steady state conditions are achieved, every day about 6 per cent of the sludge is withdrawn (by wastage) and is concurrently replaced by metabolic activities and enmeshment with a zero net increase in sludge mass. In contrast, all soluble parameters are directly affected by the hydraulics of the system, i.e. total daily flow is put through the system in 24 hours every day. This means that if for instance the soluble ammonia concentration doubles, i.e. NH_3 increases by one hundred per cent, X_n will at the most be affected by a net increase of six per cent.

The determination of μ_{nmT}, K_{mpT} and η is done by using initial estimates for these constants, e.g. by using the kinetic constants that effected closest fit with the dynamic steady state model and then changing each one of them in turn keeping the others unchanged until the best fit with the experimental response is obtained. The magnitude of f_{ca} is determined from a short sludge age single aerobic completely mixed reactor as described in Section 2.3.8.

From the discussion above it seems that the unsteady state program should be suitable for the determination of reliable nitrification and denitrification constants from an AAACMSR that approximately achieved a dynamic steady state on the day testing commenced.

Using the unsteady state program with the following input data: f_{ca} = 0,10 [mg COD.mg COD^{-1}], *average* sewage characteristics given in Table 3.10, *actual measured* influent COD = 561,5 [mg COD.ℓ^{-1}], *actual measured* influent TKN = 52,9 [mg N.ℓ^{-1}], *actual measured* alkalinity = 401,7 [mg $CaCO_3$.ℓ^{-1}], nitrification and denitrification kinetic constants that effected closest fit between experimental and simulated responses by using the dynamic steady state program with *average* influent load as input data, i.e. K_{mp20} = 3,0 [mg COD.mg VSS^{-1}.d^{-1}], η = 0,38, μ_{nm20} = 0,33 [d^{-1}] and, with the following dynamic steady state starting values taken from the dynamic steady state computer simulation for experiment EST 21: S_{bp} = 6,264 [mg COD.ℓ^{-1}], X_s = 73,34 [mg VSS.ℓ^{-1}], X_a = 1227,0 [mg VSS.ℓ^{-1}], X_e = 776,25 [mg VSS.ℓ^{-1}], X_i = 1348,9 [mg VSS.ℓ^{-1}] and X_n = 63,08 [mg VSS.ℓ^{-1}], together with the *actual measured* starting values for NO_3, NON, NH_3 and Alk. (given in Table 3.11), very good correlation was obtained between the predicted and observed responses given in Fig. 3.8b.

Comparing the predictive power of the dynamic steady state model with that of the unsteady model for experiment EST 21, Figs. 3.8 (a and b), respectively, the nitrate and alkalinity responses are *much* more closely predicted by the unsteady model. This can be attributed to the inadequacy of the dynamic steady state model to accommodate a combination of deviations, the one from ideal dynamic steady state *average influent TKN load* and the other from dynamic

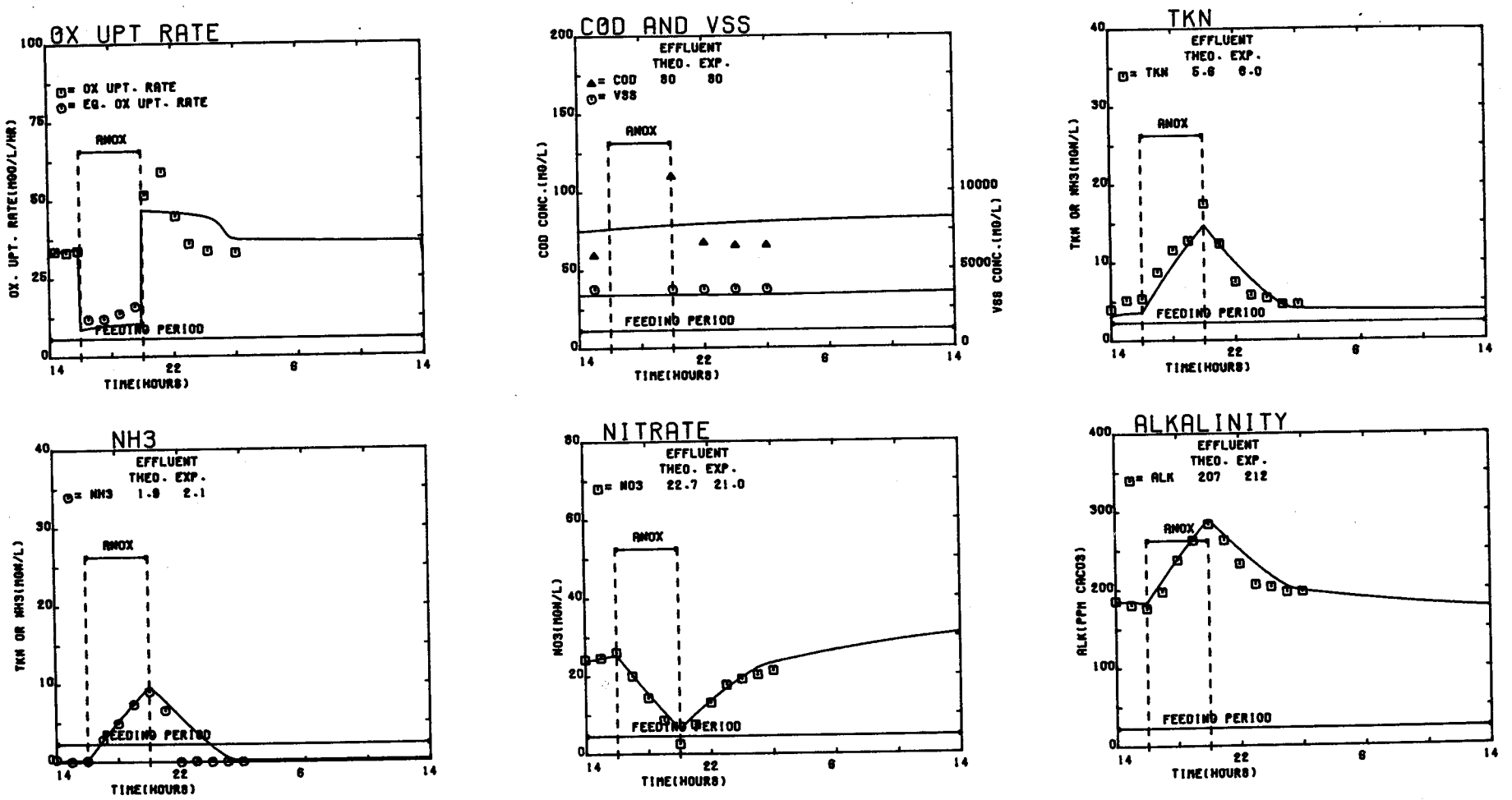

Fig.3.8b Closest fit of the observed response of an AAACMSRS under constant flow and load using the unsteady state program at 14,7°C, R_s = 15 days, f_{ca}=0,10 [mgCOD.mgCOD^{-1}], pH=7,2, with a single anoxic period of 4 hours in 24 (Experiment EST 21).

steady state *starting values* for nitrate and alkalinity. It is important to note that even though the unsteady state program gave a better correlation with observed response than the dynamic steady state program, it made use of steady state starting values for S_{bp}, X_s, X_a, X_e, X_i and X_n which can *not* be *directly* measured.

In simulations of experiment EST 21 the kinetic constants that effected closest fit with the dynamic steady state model also effected closest fit with the unsteady model, however the nitrate and alkalinity responses were much more closely fitted when using the unsteady model. Hence when operating under steady state or close to steady state conditions, depending on how closely ideal steady state has been attained, either the dynamic steady state model is sufficiently accurate in predicting the nitrification and denitrification constants from an AAACMSR system or the unsteady state model must be used *in conjunction with* its dynamic steady state counterpart.

3.3.4 Application of a CMSR to the determination of the empirical denitrification constants for a predenitrification system

Design of any predenitrification system is normally based on the empirical approach [see Eq.(2a)]. Hence, from a practical point of view it is advantageous to know the values of the denitrification constants. These are: (1) f_{ca} that determines the nitrate removal due to utilization of the easily biodegradable substrate, and (2) K_{2T} that determines the nitrate removal due to utilization of slowly biodegradable substrate.

Considering experiment EST 32, it has been shown in Section 2.3.8 that f_{ca} could be determined by employing a short sludge age completely mixed aerobic reactor under cyclic square wave flow and load. Following the procedure described in Section 2.3.8 the magnitude of f_{ca} was estimated as $f_{ca} = 0{,}10$ [mg COD.mg COD^{-1}] without the aid of a computer. In Section 3.3.2a(IV) the daily nitrate removal due to utilization of slowly biodegradable COD, ΔN_{sbp}, is given by Eq. (3.14) which requires knowledge of the total daily nitrate removal, ΔN and the daily nitrate removal due to the utilization of easily biodegradable COD, ΔN_{sbs}.

The value of ΔN_{sbs} is evaluated using Eq. (3.15), i.e.

$\Delta N_{sbs} = 2,5.2.365,5.0,10.(1-1,54.0,45)/2,86 = 19,6$ [mg $N.d^{-1}$].

The value of ΔN is calculated from the estimated denitrification reaction rate during the anoxic period given in Table 3.6. From Table 3.6,

$\Delta N = 3,4.1.15 + 3,0.1.15 = 96$ [mg $N.d^{-1}$].

Hence from Eq. (3.14)

$\Delta N_{sbp} = \Delta N - \Delta N_{sbs} = 96-19,6 = 76,4$ [mg $N.d^{-1}$].

The rate of nitrate removal due to utilization of slowly biodegradable COD over the 2 hour anoxic period, $r_{N,sbp}$ is

$r_{N,sbp} = \Delta N_{sbp}/(t_a.V) = 76,4/(2.15) = 2,55$ [mg $N.\ell^{-1}.h^{-1}$].

Comparing $r_{N,sbp}$ with Eq. (2a) it follows that

$r_{N,sbp} = \Delta N_2/R_1 = K_{2T}.X_a$

Hence, with the previously accepted

$X_a = 1259$ [mg $VSS.\ell^{-1}$],

K_{2T} can be evaluated at 14°C as

$K_{2_{14}} = r_{N,sbp}/X_a = 2,55/1259 = 2,03.10^{-3}$ [mg $N.mg\ VSS^{-1}.h^{-1}$]

i.e.,

$K_{2_{14}} = 0,049$ [mg $N.mg\ VSS^{-1}.d^{-1}$].

It is important to note that K_{2T} can always be determined manually regardless of the operational conditions as it does not require knowledge of K_{mpT}, K'_{mpT} or X_s. However extrapolation of experimental results to other operational conditions is only possible by computer simulations.

CHAPTER 4

CONCLUSIONS

This investigation was concerned with the development of different experimental set-ups and operational procedures in search for accurate and reliable evaluation of the kinetic constants and sewage characteristics that influence nitrification (μ_{nmT}) and denitrification (K'_{mpT} and f_{ca}).

Two different set-ups were investigated:

(1) Series completely mixed three reactor configuration (Fig 3.1), with the first reactor anoxic, the second and third aerobic, operated under (a) constant flow and load and (b) constant flow and COD load with a varying TKN load.

(2) Single completely mixed reactor system under sequential anoxic-aerobic conditions with two modes of operation, (a) constant flow and load and (b) square wave flow and load.

Three reactor system:

The three reactor series system was operated under *constant* flow and load in an effort to eliminate the instability normally encountered when operating under cyclic flow and load. It was hypothesized that if the retention time in the first aerobic reactor was made so short that the reaction of interest was not complete, a "transient" type condition would be induced and the need for a cyclic flow and load to achieve transients could be eliminated.

Analysis of the experimental response of the system indicated that the transient condition was ill defined - estimation of the constants by calibration could be obtained only within a range of values.

To intensify the transient state it was hypothesized that if a high TKN concentration slug was introduced over a short period of time each day, theoretically a high intensity transient could be induced and because the TKN pulse flow was small, constant flow and COD load could still be maintained. This did not prove successful principally because of the difficulties encountered in ensuring

accurate metering of the TKN slug. The cyclic nature of the TKN load again was influenced by the recycle rates *as if* the TKN input was in effect under cyclic flow and load, and this resulted again in unreliable estimates of the constants. Furthermore, it was found that from a normal practice point of view to fit the simulations to the data was time consuming to the point of impracticability.

Single reactor system:

In search for alternative set-ups and operating procedures, the single reactor system subjected to alternating aerobic and anoxic conditions (by appropriate control of aeration) under constant or cyclic flow and load was investigated. This proved a more reliable set-up than the series system:

(1) The single reactor system considerably simplified operation; the need for accurate metering of the recycle flows in the series system fell away because the single recycle in the single reactor system is in fact intra-reactor and as such does not affect the kinetic response as long as there is no accumulation of sludge in the settler.

(2) Large variations of ammonia and nitrate with time could be induced by simply selecting the appropriate anoxic-aerobic time sequence.

(3) The experimental response from a single reactor system was found to be stable and reproducible.

(4) The general dynamic steady state model could be readily adapted to simulate the response of the single reactor process to any selection sequence of anoxic and aerobic periods under either constant or cyclic flow and load conditions and the constants μ_{nmT}, K_{mpT} and η could be readily determined by calibration.

(5) In the single reactor system (in contrast to the series reactor system) the whole mass of sludge is exposed to either anoxic or aerobic conditions and thereby provides a means to test the effect of the anoxic environment on nitrification organisms in the subsequent aerobic state. This showed that for anoxic and aerobic sequence of up to 4 and 20 hours respectively, under constant flow and load, no apparent effect was observed. This however

may not be the case under different operating conditions and with different sewage sources.

(6) In experiments where on the day of the test the input varied from the mean inputs for the period prior to the test, the calibration procedure was modified as follows. The process was simulated using the mean input data and the resulting output response was used as starting values for simulation of the output response on the day testing was done. The starting values of the independent parameters were either the experimentally measured values (S_u, NH_3, NON, NO_3, Alk) or, where direct measurements were not possible (for S_{bp}, Y_s, Y_a, Y_e, Y_i, Y_n), the corresponding either constant or cyclic steady state values of the general dynamic steady state model. This approach led to very successful calibration (as indicated by the close fits obtained) and hence reliable determination of the constants.

(7) It was shown possible to manually determine good estimates for μ_{nmT} from the nitrate response of a single reactor system. Manual determination was also possible for K_{mpT} and η provided the easily biodegradable COD fraction in the influent was available. Manual estimations should be of particular usefulness in cases where computer facilities are not available.

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APPENDIX A

A.1 Listing of the computer program for the dynamic steady state model.

A.2 Listing of the computer program for the unsteady state model.

A.3 Listing of the computer program used for plotting experimental and predicted responses of an alternating anoxic aerobic completely mixed single reactor system.

PROGRAM A.1

```
1     C*************************************************************************
2     C
3     C          ''THIS PROGRAMME IS THE JOINT PROPERTY OF THE
4     C          UNIVERSITY OF CAPE TOWN AND THE WATER RESEARCH
5     C          COMMISSION OF SOUTH AFRICA. BEFORE USER MAY
6     C          LEGALLY UTILIZE IT, HE MUST OBTAIN THE NECESSARY
7     C          AUTHORIZATION, I.E.:
8     C
9     C          (A) IN THE CASE OF STUDENTS AT THE UNIVERSITY OF
10    C              CAPE TOWN WHO WILL USE THE PROGRAMME FOR
11    C              EDUCATIONAL PURPOSES ONLY, THIS AUTHORIZATION
12    C              CAN BE OBTAINED FROM PROF. G. VAN R. MARAIS
13    C              OF THE UNIVERSITY OF CAPE TOWN, AND
14    C          (B) IN ALL OTHER CASES, WRITTEN AUTHORIZATION
15    C              MUST BE OBTAINED FROM BOTH THE UNIVERSITY
16    C              OF CAPE TOWN (PRIVATE BAG, RONDEBOSCH, 7700,
17    C              CAPE, SOUTH AFRICA) AND THE WATER RESEARCH
18    C              COMMISSION (P.O. BOX 824, PRETORIA, 0001,
19    C              SOUTH AFRICA)''
20    C
21    C          FOR A DETAILED GUIDE DESCRIBING THE USE OF THIS
22    C          PROGRAM REFER TO:
23    C          ' MANUAL FOR USING THE GENERAL ACTIVATED SLUDGE
24    C            SIMULATION PROGRAMS', DEPT. OF CIVIL ENG.
25    C            UNIVERSITY OF CAPE TOWN.
26    C*************************************************************************
27    C  DYNAMIC STATE MODEL OF ACTIVATED SLUDGE PROCESS FOR SERIES REACTORS
28    C  ---------------------------------------------------------------------
29    C            (INCLUDING  STORAGE OF COD,  NITRIFICATION AND
30    C                                          DENITRIFICATION
31    C          CALCULATION CHARACTERISTICS
32    C          --------------------------
33    C          THIS PROGRAMME REQUIRES THE FOLLOWING CORE STORAGE CAPACITY:-
34    C           FOR ND=241 AND NF=4*(ND-1)+1 AND NEE=NE+1
35    C           STORAGE=10*NE+23 KILOWORDS
36    C           DOUBLING ND INCREASES STORAGE REQUIREMENT BY 1.75
37    C           APPROX. CALCULATION CPU TIME ON A UNIVAC 1106 COMPUTER
38    C           FOR 100 ITERATIONS:
39    C           CPU TIME (SECONDS) =50*NE+30
40    C
41    C            KO = TIME BASE VARIABLE
42    C             M = CYCLE NUMBER MONITOR
43    C             D = NUMBER OF INTERGRATION STEPS PER DAY
44    C            DT = INTERGRATION STEP LENGTH
45    C            DD = NUMBER OF INTERGRATION STEPS PER DAY FOR NITRIFICATION
46    C           DDT = INTERGRATION STEP LENGTH FOR NITRIFICATION
47    C           RDT = RATIO OF INTERGRATION STEP LENGTHS
48    C            KH = NUMBER OF TIME STEPS PER HOUR = D/24
49    C            HK = NO. OF INTERVALS PER DAY  OF SLUDGE WASTAGE
50    C
51    C        NOTE
52    C        ----
53    C           NITROGEN CONCENTRATIONS MEASURED IN MG-N/L WITH TKN TEST
54    C           COD CONCENTRATIONS MEASURED IN MG/L OF COD
55    C           VSS CONCENTRATIONS MEASURED IN MG/L OF VSS
56    C           OXYGEN CONSUMPTIONS IN MG/L/HOUR
57    C           UNIT OF MASS IS THE MG
58    C           UNIT OF VOLUME IS THE L
59    C           UNIT OF TIME IS THE DAY
60    C           SYMBOL S REFERS TO COD
61    C           SYMBOL X REFERS TO VSS
62    C           SYMBOL N REFERS TO NITROGEN
63    C           SYMBOL O REFERS TO OXYGEN
```

```
      C
      C       DIMENSION STATEMENTS
      C       --------------------
      C
            PARAMETER NE=1
            PARAMETER NEE=2
            PARAMETER ND=241
            PARAMETER NDD=242
            COMMON/EXTC/SBS(NE,ND),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
           1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,ND),NH3(NE,ND),
           2NO3(NE,ND),SBP(NE,ND),ALK(NE,ND)
            COMMON/BLOCKC/Q(NEE,NDD),V(NE),SBI(ND),SUI(ND),NIT(NE,ND),
           1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),ALKI(ND),
           2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(ND),SYNTH(NE,ND),QAV(NEE),
           3ANPOT(NE,ND),AMON(NE,ND),DSFCTR(NE)
            CHARACTER IMFT*19/'((20X,I4, (E13.5)))'/,CH*1
            REAL KVT,KMPT,KSPT,KMST,KSST,KRT,KNT
            REAL NUI,NONI,NH3I,NO3I,NIT
            REAL NU,NON,NH3,NO3
            INTEGER D,DD,HK,TYPE,RESULT
            DOUBLE PRECISION DT,DDT,RDT
            DIMENSION STI(ND),STQ(ND),
           &INIT(NE),ANOX(NE),AROB(NE),IFREQ(NE),INTDN(NE),FANOX(NE)
            REAL NTI(ND),NTQ(ND),NO3Q(ND),NXII(ND)
            REAL NTIAV,NUIAV,NONIAV,NO3IAV,NH3IAV,NXIIAV
            REAL NTQAV,NO3QAV
            REAL NTIMAX,NO3IAX,NTQMAX,NO3QAX
            REAL NTI0,NTI00,NO3I0,NO3I00,LFP
            DIMENSION RA(NE),RN(NE),LRSD(NE),NTDN(NE,ND),ALKQ(ND)
            REAL KV20,KMP20,KSP20,KMS20,KSS20,KNMAX,KN20,KR20
            DIMENSION STOSBP(NE,ND),STOXV(NE,ND),STNO3(NE,ND),STOXN(NE,ND)
            DIMENSION KO(ND),WQ(NE,ND),STOXS(NE,ND),
           1OC(NE,ND),ON(NE,ND),OT(NE,ND),ST(NE,ND),RXS(NE,ND)
            REAL NT(NE,ND)
            DIMENSION SBSAV(NE),ODAV(NE),OCAV(NE),RNO3(NE),ALKAV(NE),AMAV(NE),
           1ONAV(NE),OTAV(NE),STAV(NE),SUAV(NE),SBPAV(NE),
           2XAAV(NE),XEAV(NE),XSAV(NE),XIAV(NE),XVAV(NE),
           3XNAV(NE),RXSAV(NE),NAME(NE),LNAME(3),APTAV(NE),APTNR(NE)
            REAL NONAV(NE),NTAV(NE),NO3AV(NE),NH3AV(NE),NUAV(NE),NSWAV(NE)
            REAL NONSS,NUSS,NO3SS,NH3SS
      C
      C           INPUT OF DATA
      C           -------------
      C         TYPE = LOGICAL NUMBER DESCRIBING INFLUENT LOAD PATTERN
      C           IF = 1   SINE WAVE LOAD PATTERN
      C           IF = 2   SQUARE WAVE LOAD PATTERN
      C           IF = 3   GENERAL LOADING PATTERN
      C       RESULT = LOGICAL NUMBER TO DIRECT OUTPUT
      C           IF = 1    PRINT RESULTS
      C           IF = 2    PLOT RESULTS
      C           IF = 0    PLOT AND PRINT RESULTS
      C          KOM = TIME AT WHICH TIME BASE COUNTER COMMENCES
      C          END = NUMBER OF HOURS FOR WHICH PLOTTING IS REQUIRED
      C          NDH = NUMBER OF NODES OF THE 'KH' INTERVALS REQUIRED
      C                  FOR PLOTTING  E.G.: IF PLOTTING IS REQUIRED
      C                  FOR A PERIOD OF 18 HOURS, NDH=18*KH+1
      C         CRIT = MAXIMUM ERROR ALLOWED BETWEEN CONSECUTIVE DAYS'
      C                VALUES OF PROCESS VARIABLES TO TEST FOR CONVERGENCE
        100 FORMAT ( )
            READ(8,100)TYPE,RESULT,KOM,NDH,CRIT
            WRITE(5,100)TYPE,RESULT,KOM,NDH,CRIT
            IF(TYPE.EQ.1) GO TO 111
            IF(TYPE.EQ.2) GO TO 112
            IF(TYPE.EQ.3) GO TO 113
```

```
      111 READ(8,100)PI
          WRITE(5,100)PI
      C         VF = VOLUME OF FEED PER DAY
      C         Q0 = AVERAGE INFLUENT FLOW FOR SINE WAVE PATTERN
      C       STI0 = INFLUENT COD CONCENTRATION DURING PEAK FLOW PERIOD FOR
      C              SQUARE WAVE PATTERN OR AVERAGE FOR SINE WAVE PATTERN
      C       NTI0 = INFLUENT TKN CONCENTRATION DURING PEAK FLOW PERIOD FOR
      C              SQUARE WAVE PATTERN OR AVERAGE FOR SINE WAVE PATTERN
      C      NO3I0 = INFLUENT NO3 CONCENTRATION DURING PEAK FLOW PERIOD FOR
      C              SQUARE WAVE PATTERN OR AVERAGE FOR SINE WAVE PATTERN
      C      ALKI0 = INFLUENT ALK CONCENTRATION DURING PEAK FLOW PERIOD FOR
      C              SQUARE WAVE PATTERN OR AVERAGE FOR SINE WAVE PATTERN
      C      STI00 = INFLUENT COD CONCENTRATION DURING BASE FLOW PERIOD
      C      NTI00 = INFLUENT TKN CONCENTRATION DURING BASE FLOW PERIOD
      C     NO3I00 = INFLUENT NO3 CONCENTRATION DURING BASE FLOW PERIOD
      C     ALKI00 = INFLUENT ALK CONCENTRATION DURING BASE FLOW PERIOD
      C        LFP = LENGTH OF FEED PERIOD (SQUARE WAVE)
      C         BQ = BASE FLOW RATE IN SQUARE WAVE PATTERN
      C      START = INTERVAL BETWEEN 'KOM' AND THE BEGINNING OF THE
      C              FEEDING PERIOD (HOURS).
      C      AROB = LENGTH OF AERATED PERIOD (HOURS)
      C      ANOX = LENGTH OF UNAERATED PERIOD (HOURS)
      C      INIT = INTERVAL BETWEEN 'KOM' AND 'ANOX' DURING WHICH THE REACTO
      C             WAS AERATED (HOURS)
      C       IFREQ = NUMBER OF PAIRS OF UNAERATED-AERATED INTERVALS
      C
          READ(8,100)Q0,STI0,NTI0,NO3I0,ALKI0,VARQ,VARSTI,VARNTI,VNO3I,VALKI
          WRITE(5,100)Q0,STI0,NTI0,NO3I0,ALKI0,VARQ,VARSTI,VARNTI,VNO3I,VALK
          GO TO 113
      112 READ(8,100)VF,STI0,NTI0,NO3I0,ALKI0,BQ,STI00,NTI00,NO3I00,ALKI00,
         &LFP,START
          WRITE(5,100)VF,STI0,NTI0,NO3I0,ALKI0,BQ,STI00,NTI00,NO3I00,ALKI00,
         &LFP,START
      C         KINETIC CONSTANTS
      C         ----------------
      C         AN EXTRA T OR 20 INDICATES VALUES AT T OR 20 DEG. C
      C          KV = MAX. RATE OF COD TRANSFER FROM SEWAGE INTO STORAGE
      C          KR = RATE OF CONVERSION OF ORGANIC N TO SALINE NH3
      C          KM = MAX. RATE OF  ORGANISM SYNTHESIS FROM STORED COD
      C            ('KMS' AND 'KMP' REFER TO EASILY BIODEG.(SOLUBLE) AND
      C              SLOWLY BIODEG.(PARTICULATE) COD FRACTIONS, RESPECTIVELY)
      C          KS = SATURATION COEF. FOR EASILY BIODEG. COD  UTILIZATION
      C          UM = MAXIMUM GROWTH RATE OF NITRIFYING ORGANISMS
      C          KN = SATURATION COEF. FOR NH3  UTILIZATION
      C          BH = DEATH RATE CONSTANT
      C          BN = ENDOGENOUS RESPIRATION RATE FOR NITRIFICATION
      C        THEA = TEMPERATURE DEPENDENCY CONSTANT FOR EASILY BIODEG. COD
      C        THES = TEMPERATURE DEPENDENCY CONSTANT FOR SYNTHESIS
      C        THEE = TEMPERATURE DEPENDENCY CONSTANT FOR DEATH
      C        PHIN = PH DEPENDENCY CONSTANT FOR NITRIFICATION
      C        THEN = TEMPERATURE DEPENDENCY CONSTANT FOR NITRIFICATION
      C        THEZ = CONSTANT FOR NO TEMPERATURE DEPENDENCY
      C          YH = YIELD OF ORGANISMS FROM COD UTILIZED
      C          YN = ACTIVE MASS YIELD OF NITRIFYING ORGANISMS FROM AMMONIA
      C           F = UNBIODEG. FRACTION OF ORGANISM
      C          FR = MAXIMUM FRACTION OF STORED COD (AS VSS) TO ACTIVE
      C             ORGANISM MASS
      C          FN = FRACTION OF CARBONACEOUS CELL MASS AS N
      C         FNS = FRACTION OF NITROGEN ASSOCIATED WITH STORED COD
      C           P = COD EQUIVALENT OF VSS
      C         FBS = FRACTION EASILY BIODEG./TOTAL BIODEG. INFL.COD
      C         FOE = FRACTION OF N RELEASED BY ENDOGENOUS RESPIRATION
      C             AS ORGANIC NITROGEN
      C         FOS = FRACTION OF NITROGEN REQUIRED FOR CELL SYNTHESIS
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      C                AS ORGANIC NITROGEN
      C          FACT = RATIO BETWEE KMP IN ANOX. AND AROB. ENVIRONMENT
      C           FCS = FRACTION OF LYSED MATERIAL RELEASED AS SBS
      C
      C
  113 READ(8,100) KV20,KMP20,KSP20,KMS20,KSS20,UMAX,KNMAX,BH20,BN20,
     &KR20,FOS,FBS,FR,YH,YN,F,P,FN,FOE,FACT,FCS
          READ(8,100)RS,NR,D,NJ,FUS,FUP,UN,SN
          READ(8,100)THEA,THEM,THES,THEE,PHIN,THEN,THEZ,TEMP,PH
          READ(8,100) (V(J),LRSD(J),J=1,NR,1)
          WRITE(5,100) (V(J),LRSD(J),J=1,NR,1)
          READ(8,100) ICSD,ISSD,NRSD,LINI,LSRI,LARI,LARO,LBRI,LBRO,SR,AR,BR
          WRITE(5,100) ICSD,ISSD,NRSD,LINI,LSRI,LARI,LARO,LBRI,LBRO,SR,AR,BR
          READ(8,100)(INIT(J),ANOX(J),AROB(J),IFREQ(J),J=1,NR)
          KH=D/24
          NL=D+1
          NLL=D+2
          DD=NJ*D
          NRR=NR+1
      C
      C           SEWAGE CHARACTERISTICS
      C           ----------------------
      C         NM,NN = LIMITS OF PEAK FLOW PERIOD
      C          QMAX = MAXIMUM FLOW VALUE OF THE DAY
      C        STIMAX = MAXIMUM COD CONCENTRATION VALUE OF THE DAY
      C       NTIMAX = MAXIMUM TKN CONCENTRATION VALUE OF THE DAY
      C       NO3IAX = MAXIMUM NO3 CONCENTRATION VALUE OF THE DAY
      C       ALKIAX = MAXIMUM ALK CONCENTRATION VALUE OF THE DAY
      C            Q = INFLUENT FLOW
      C          STI = TOTAL INFLUENT COD
      C          NTI = TOTAL INFLUENT TKN
      C          STQ = TOTAL INFLUENT COD LOAD
      C          NTQ = TOTAL INFLUENT TKN LOAD
      C         NO3Q = TOTAL INFLUENT NO3 LOAD
      C         ALKQ = TOTAL INFLUENT ALK LOAD
      C         NONI = INFLUENT ORGANIC NITROGEN CONCENTRATION
      C         NH3I = INFLUENT AMMONIA CONCENTRATION
      C         NO3I = INFLUENT NITRATE CONCENTRATION
      C         ALKI = INFLUENT ALKALINITY CONCENTRATION
      C          NUI = UNBIODEGRADABLE FRACTION OF SEWAGE N
      C         NXII = UNSABLE N IN INERT MATERIAL IN INFLUENT
      C          XII = UNBIODEG. SOLID FRACTION OF SEWAGE COD AS VSS
      C          SBI = BIODEG. FRACTION OF SEWAGE COD
      C          SUI = UNBIODEG. SOLUBLE FRACTION OF SEWAGE COD
      C          FUS = FRACTION OF SOLUBLE UNBIODEG. COD
      C          FUP = FRACTION OF SOLID UNBIODEG. COD AS VSS
      C           UN = UNBIODEGRADABLE FRACTION OF N
      C           SN = FRACTION OF TKN AS AMMONIA
      C       STQMAX = MAXIMUM COD LOAD VALUE OF THE DAY
      C       NTQMAX = MAXIMUM TKN LOAD VALUE OF THE DAY
      C       NO3QAX = MAXIMUM NO3 LOAD VALUE OF THE DAY
      C       ALKQAX = MAXIMUM ALK LOAD VALUE OF THE DAY
      C           PQ = PEAK FLOW RATE IN SQUARE WAVE PATTERN
      C       VARSTI = AMPLITUDE OF INPUT COD CONC. WAVE (SINE WAVE)
      C       VARNTI = AMPLITUDE OF INPUT TKN CONC. WAVE (SINE WAVE)
      C        VNO3I = AMPLITUDE OF INPUT NO3 CONC. WAVE (SINE WAVE)
      C        VALKI = AMPLITUDE OF INPUT ALK CONC. WAVE (SINE WAVE)
      C         VARQ = AMPLITUDE OF INFLUENT FLOW WAVE (SINE WAVE)
      C       VARSTL = AMPLITUDE OF INFLUENT COD LOAD WAVE (SINE WAVE)
      C       VARNTL = AMPLITUDE OF INFLUENT TKN LOAD WAVE (SINE WAVE)
      C       VRNO3L = AMPLITUDE OF INFLUENT NO3 LOAD WAVE (SINE WAVE)
      C       VRALKL = AMPLITUDE OF INFLUENT ALK LOAD WAVE (SINE WAVE)
      C
      C           PROCESS CHARACTERISTICS
```

```
256       C           ----------------------
257       C
258       C          TEMP = OPERATING TEMPERATURE OF MIXED LIQUOR
259       C            PH = OPERATING PH OF MIXED LIQUOR
260       C           RSM = MINIMUM SLUDGE AGE FOR NITRIFICATION
261       C            RN = NOMINAL HYDRAULIC RETENTION TIME IN REACTORS
262       C            RA = ACTUAL HYDRAULIC RETENTION TIME IN REACTORS
263       C           TRN = TOTAL HYDRAULIC RETENTION TIME OF PROCESS
264       C            SR = SLUDGE UNDERFLOW RECYCLE RATIO TO AVERAGE INFLUENT FLOW
265       C           QSR = SLUDGE UNDERFLOW RECYCLE RATE
266       C            AR = MIXED LIQUOR RECYCLE RATIO TO AVERAGE INFLUENT FLOW
267       C           QAR = MIXED LIQUOR RECYCLE RATE
268       C            NR = NUMBER OF REACTORS IN SERIES
269       C           NRR = NUMBER OF REACTORS IN SERIES INCLUDING CLARIFIER
270       C          NRSD = NUMBER OF REACTORS FROM WHICH SLUDGE IS WASTED
271       C          LRSD = LOGICAL NUMBER DESCRIBING SLUDGE WASTAGE
272       C                 FROM REACTORS
273       C            IF = 1  SLUDGE TO BE WASTED FROM REACTOR
274       C            IF = 0  NO SLUDGE TO BE WASTED FROM REACTOR
275       C          ICSD = TIME AT WHICH SLUDGE WASTAGE COMMENCES
276       C          ISSD = TIME AT WHICH SLUDGE WASTAGE TERMINATES
277       C             V = VOLUME OF REACTOR
278       C            VP = TOTAL VOLUME OF PROCESS
279       C            WQ = SLUDGE WASTE FLOW
280       C      N.B.  THE SLUDGE WASTE FLOW MAY NEVER BE GREATER THAN
281       C             THE INFLUENT FLOW AT ANY INERVAL OF THE DAY
282       C        I.E. THE EFFLUENT FLOW FROM A REACTOR MAY NEVER BE LESS
283       C             THAN ZERO AT ANY INTERVAL OF THE DAY
284       C
285             IF(TYPE.EQ.1) GO TO 115
286             IF(TYPE.EQ.2) GO TO 116
287             READ(8,100) (Q(1,I),I=1,NL,KH)
288             WRITE(5,100) (Q(1,I),I=1,NL,KH)
289             READ(8,100) (STI(I),I=1,NL,KH)
290             WRITE(5,100) (STI(I),I=1,NL,KH)
291             READ(8,100) (NTI(I),I=1,NL,KH)
292             WRITE(5,100) (NTI(I),I=1,NL,KH)
293             READ(8,100) (NO3I(I),I=1,NL,KH)
294             WRITE(5,100) (NO3I(I),I=1,NL,KH)
295             READ(8,100) (ALKI(I),I=1,NL,KH)
296             WRITE(5,100) (ALKI(I),I=1,NL,KH)
297             IF(TYPE.EQ.3) GO TO 117
298           115 DO 8 I=1,NL,KH
299             KL=(I-1)/KH
300             DUM=SIN(2*PI*(KL-8)/24)
301             Q(1,I)=Q0*(1+VARQ*DUM)
302             STI(I)=STI0*(1+VARSTI*DUM)
303             NTI(I)=NTI0*(1+VARNTI*DUM)
304             NO3I(I)=NO3I0*(1+VNO3I*DUM)
305             ALKI(I)=ALKI0*(1+VALKI*DUM)
306           8 CONTINUE
307       C
308       C          INTERPOLATION OF STI, NO3I, Q AND NTI AT REQUIRED INTERVALS
309       C          ------------------------------------------------------------
310       C
311           117 DO 25 I=1,24
312             KI=KH*I+1
313             KJ=KH*(I-1)+1
314             DIFSTI=(STI(KI)-STI(KJ))/KH
315             DIFFQ=(Q(1,KI)-Q(1,KJ))/KH
316             DIFNTI=(NTI(KI)-NTI(KJ))/KH
317             DNO3I=(NO3I(KI)-NO3I(KJ))/KH
318             DALKI=(ALKI(KI)-ALKI(KJ))/KH
319             DO 25 J=2,KH,1
```

```
320           KK=KJ+J-1
321           STI(KK)=STI(KJ)+(J-1)*DIFSTI
322           Q(1,KK)=Q(1,KJ)+(J-1)*DIFFQ
323           NTI(KK)=NTI(KJ)+(J-1)*DIFNTI
324           NO3I(KK)=NO3I(KJ)+(J-1)*DNO3I
325           ALKI(KK)=ALKI(KJ)+(J-1)*DALKI
326        25 CONTINUE
327           GO TO 118
328       116 PQ=BQ+(VF-BQ)*24.0/LFP
329           DO 24 I=1,NL,1
330           NTI(I)=NTI00
331           STI(I)=STI00
332           Q(1,I)=BQ
333           NO3I(I)=NO3I00
334           ALKI(I)=ALKI00
335        24 CONTINUE
336           NM=INT(START)*KH+1
337           END=START+LFP
338           NN=NM+LFP*KH
339           DO 23 I=NM,NN,1
340           STI(I)=STI0
341           Q(1,I)=PQ
342           NTI(I)=NTI0
343           NO3I(I)=NO3I0
344           ALKI(I)=ALKI0
345        23 CONTINUE
346       118 DO 1 I=1,NL
347           STQ(I)=STI(I)*Q(1,I)
348           NTQ(I)=NTI(I)*Q(1,I)
349           NO3Q(I)=NO3I(I)*Q(1,I)
350           ALKQ(I)=ALKI(I)*Q(1,I)
351           SUI(I)=FUS*STI(I)
352           NUI(I)=UN*NTI(I)
353           XII(I)=FUP*STI(I)
354           NXII(I)=XII(I)*FN
355           NH3I(I)=SN*NTI(I)
356           NONI(I)=NTI(I)-NUI(I)-NXII(I)-NH3I(I)
357         1 SBI(I)=STI(I)*(1.0-FUS-FUP*P)
358     C
359     C       CALCULATION OF AVERAGE SEWAGE CHARACTERISTICS
360     C        ---------------------------------------------
361     C
362           SUMQ=0
363           SUMSTI=0
364           SUMNTI=0
365           SNO3I=0.0
366           SALKI=0.0
367           QMAX=0.0
368           STIMAX=0.0
369           SUMSTQ=0.0
370           STQMAX=0.0
371           SUMNTQ=0.0
372           NTQMAX=0.0
373           NTIMAX=0.0
374           SNO3Q=0.0
375           NO3QAX=0.0
376           NO3IAX=0.0
377           SALKQ=0.0
378           ALKQAX=0.0
379           ALKIAX=0.0
380           DO 2 I=1,D,1
381           SUMNTI=SUMNTI+NTI(I)
382           SNO3I=SNO3I+NO3I(I)
383           SALKI=SALKI+ALKI(I)
```

```
384             SUMSTI=SUMSTI+STI(I)
385             SUMSTQ=SUMSTQ+STQ(I)
386             SUMNTQ=SUMNTQ+NTQ(I)
387             SNO3Q=SNO3Q+NO3Q(I)
388             SALKQ=SALKQ+ALKQ(I)
389             IF(STQ(I).GT.STQMAX) STQMAX=STQ(I)
390             IF(NTQ(I).GT.NTQMAX) NTQMAX=NTQ(I)
391             IF(NO3Q(I).GT.NO3QAX) NO3QAX=NO3Q(I)
392             IF(ALKQ(I).GT.ALKQAX) ALKQAX=ALKQ(I)
393             IF(Q(1,I).GT.QMAX) QMAX=Q(1,I)
394             IF(STI(I).GT.STIMAX) STIMAX=STI(I)
395             IF(NTI(I).GT.NTIMAX) NTIMAX=NTI(I)
396             IF(NO3I(I).GT.NO3IAX) NO3IAX=NO3I(I)
397             IF(ALKI(I).GT.ALKIAX) ALKIAX=ALKI(I)
398           2 SUMQ=SUMQ+Q(1,I)
399             QAV(1)=SUMQ/D
400             STQAV=SUMSTQ/D
401             NTQAV=SUMNTQ/D
402             NO3QAV=SNO3Q/D
403             ALKQAV=SALKQ/D
404             IF(TYPE.EQ.2) GO TO 119
405             NTIAV=SUMNTI/D
406             STIAV=SUMSTI/D
407             NO3IAV=SNO3I/D
408             ALKIAV=SALKI/D
409             GO TO 120
410         119 STIAV=STQAV/VF
411             NTIAV=NTQAV/VF
412             NO3IAV=NO3QAV/VF
413             ALKIAV=ALKQAV/VF
414         120 SBIAV=STIAV*(1.0-FUS-FUP*P)
415             SUIAV=FUS*STIAV
416             NUIAV=NTIAV*UN
417             XIIAV=FUP*STIAV
418             NXIIAV=FN*XIIAV
419             NH3IAV=SN*NTIAV
420             NONIAV=NTIAV-NXIIAV-NUIAV-NH3IAV
421             QSR=SR*QAV(1)
422             QAR=AR*QAV(1)
423             QBR=BR*QAV(1)
424             IF(TYPE.EQ.2) GO TO 121
425             IF(TYPE.EQ.3) GO TO 121
426             VARSTL=STQMAX/STQAV-1.00
427             VARNTL=NTQMAX/NTQAV-1.00
428             VRNO3L=NO3QAX/NO3QAV-1.00
429             VRALKL=ALKQAX/ALKQAV-1.00
430             IF(VRNO3L.LT.0.0) VRNO3L=0.0
431             IF(VRALKL.LT.0.0) VRALKL=0.0
432             IF(TYPE.EQ.1) GO TO 121
433             VARQ=QMAX/QAV(1)-1.00
434             VARSTI=STIMAX/STIAV-1.00
435             VARNTI=NTIMAX/NTIAV-1.00
436             VNO3I=NO3IAX/NO3IAV-1.00
437             VALKI=ALKIAX/ALKIAV-1.00
438             IF(VNO3I.LT.0.0) VNO3I=0.0
439             IF(VALKI.LT.0.0) VALKI=0.0
440         121 CONTINUE
441       C
442       C             CALCULATE TOTAL AND AEROBIC VOLUMES
443       C             -----------------------------------
444       C
445             DO 37 J=1,NR,1
446             DO 37 I=1,NL,1
447             NTDN(J,I)=1
```

```
448      37    CONTINUE
449            VP=0.0
450            DO 133 J=1,NR,1
451            NAMBA=IFREQ(J)
452            VP=VP+V(J)
453            DO 133 I=1,NL,1
454            DO 133 II=1,NAMBA,1
455            IB=(INIT(J)+(II-1)*(ANOX(J)+AROB(J)))*KH+1
456            IE=(INIT(J)+(II-1)*(ANOX(J)+AROB(J))+ANOX(J))*KH+1
457            IF(I.GE.IB.AND.I.LT.IE) NTDN(J,I)=0
458            NTDN(J,NL)=NTDN(J,1)
459          133 CONTINUE
460            JJ=3
461            DO 77 J=1,NR,1
462            INTDN(J)=0
463            DO 77 I=1,NL,1
464            INTDN(J)=INTDN(J)+NTDN(J,I)
465      77    CONTINUE
466            LNAME(1)='AROB'
467            LNAME(2)='ANOX'
468            LNAME(3)='ONOF'
469            SANOX=0.0
470            DO 78 J=1,NR,1
471            IF(INTDN(J).EQ.0) JJ=2
472            IF(INTDN(J).EQ.NL) JJ=1
473            NAME(J)=LNAME(JJ)
474            FANOX(J)=1.0-(FLOAT(INTDN(J)))/(FLOAT(NL))
475            SANOX=SANOX+FANOX(J)*V(J)/VP
476      78    CONTINUE
477      C
478      C             ADJUST TEMPERATURE AND PH DEPENDENT CONSTANTS
479      C             ---------------------------------------------
480      C
481            IF(PH.LT.8.0) UM20=UMAX
482            IF(PH.LT.7.2) UM20=UMAX*(PHIN)**(PH-7.20)
483            IF(PH.LT.8.0) KN20=KNMAX
484            IF(PH.LT.7.2) KN20=KNMAX*(PHIN)**(7.20-PH)
485            IF(TYPE.NE.1) VARNTL=0.0
486            UMT=UM20*(THEN)**(TEMP-20.0)
487            KNT=KN20*(THEN)**(TEMP-20.0)
488            KSPT=KSP20*(THES)**(20.0-TEMP)
489            KMPT=KMP20*(THEM)**(TEMP-20.0)
490            KSST=KSS20*(THEZ)**(TEMP-20.0)
491            DO 17 J=1,NR,1
492            DO 17 I=1,NL,1
493            IF(NTDN(J,I).EQ.0) GO TO 19
494         17 CONTINUE
495            KMST=10.0
496            GO TO 20
497         19 KMST=KMS20*(THEA)**(TEMP-20.0)
498         20 KRT=KR20*(THEE)**(TEMP-20.0)
499            KVT=KV20*(THEE)**(TEMP-20.0)
500            BHT=BH20*(THEE)**(TEMP-20.0)
501            BNT=BN20*(THEE)**(TEMP-20.0)
502            RSM=1.0/((UMT/(1.0+(KNT/(SN*NTIAV))))-BNT)
503            RSA=RS*(1.0-SANOX)
504            TRN=VP/QAV(1)
505            FNS=NONIAV/SBIAV
506            CC=(1.0-F)*BHT*YH*RS/(1.0+BHT*(1.0-YH*P*(1.0-F))*RS)
507            FNS=(FNS*(1.0-FBS)+FN*CC)/((1.0-FBS)+P*CC)
508      C
509      C               CALCULATE INITIAL CONDITIONS (PARTICULAR INTEGRAL)
510      C*****************************************************************
511            CALL PARMOD(YH,FBS,RS,RSA,BHT,KVT,TRN,KMPT,KSPT,KMST,KSST,
```

```
512           1P,F,FN,FNS,KRT,KNT,BNT,UMT,YN,SR,AR,BR,FACT,FR,
513           2SBIAV,SUIAV,XIIAV,NUIAV,NONIAV,NTIAV,NO3IAV,STQAV,ALKIAV,
514           3XASS,XSSS,XESS,XISS,XVSS,XNSS,SBPSS,SBSSS,SUSS,
515           4NONSS,NH3SS,NO3SS,NUSS,ALKSS,VARNTL)
516      C*****************************************************************
517            FACTC=STQAV/(STIAV*QAV(1))
518            FACTN=NTQAV/(NTIAV*QAV(1))
519            XASS=FACTC*XASS
520            XSSS=FACTC*XSSS
521            XESS=FACTC*XESS
522            XISS=FACTC*XISS
523            XVSS=FACTC*XVSS
524            XNSS=FACTN*XNSS
525            CRITXV=CRIT*XVSS
526            IF(CRITXV.LT.CRIT) CRITXV=CRIT
527            CRITXS=CRIT*XSSS
528            IF(CRITXS.LT.CRIT) CRITXS=CRIT
529            CRISBP=CRIT*SBPSS
530            IF(CRISBP.LT.CRIT) CRISBP=CRIT
531            CRINO3=CRIT*NO3SS
532            IF(CRINO3.LT.CRIT) CRINO3=CRIT
533            CRITXN=CRIT*XNSS
534            IF(CRITXN.LT.CRIT) CRITXN=CRIT
535      C
536      C          GENERAL NOTATION FOR PROCESS VARIABLES IN REACTOR
537      C          ------------------------------------------------
538      C
539      C          SBP = BIODEGRADABLE PARTICULATE COD
540      C          SBS = BIODEGRADABLE SOLUBLE COD
541      C           SU = UNBIODEGRADABLE COD
542      C           ST = TOTAL COD
543      C           XS = STORED COD
544      C           XA = ACTIVE ORGANISMS
545      C           XE = INERT RESIDUE FROM DECAYING ORGANISMS
546      C           XI = INERT MATERIAL FROM SEWAGE
547      C           XN = ACTIVE NITROSOMONAS
548      C           XV = TOTAL VSS
549      C           OA = OXYGEN CONSUMPTION RATE FOR ADSORPTION OF COD
550      C           OS = OXYGEN CONSUMPTION RATE FOR SYNTHESIS
551      C           OE = OXYGEN CONSUMPTION RATE FOR ENDOGENOUS RESPIRATION
552      C           OC = TOTAL CARBONACEOUS OXYGEN CONSUMPTION RATE
553      C           ON = OXYGEN CONSUMPTION FOR NITRIFICATION
554      C           OT = TOTAL OXYGEN CONSUMPTION RATE
555      C          NSW = NITROGEN REMOVED IN SLUDGE WASTAGE PER DAY
556      C           NT = TOTAL TKN IN REACTOR
557      C           NU = UNBIODEGRADABLE TKN IN REACTOR
558      C          NON = ORGANIC NITROGEN CONCENTRATION  IN REACTOR
559      C          NH3 = AMMONIA CONCENTRATION IN REACTOR
560      C          NO3 = NITRATES CONCENTRATION IN REACTOR
561      C          ALK = ALKALINITY CONCENTRATION IN REACTOR
562      C          RXS = RATE OF CHANGE OF STORED COD (AS MG-VSS/L/D)
563      C          SCI = ENERGY ENTERING STORAGE FROM LIQUID PHASE (MG-COD/L)
564      C         SCVO = ENERGY REMOVED FROM STORAGE DUE TO CELL SYNTHESIS (MG-V
565      C
566      C          THE SUFFIX 'AV' AFTER A SYMBOL INDICATES DAILY AVERAGE
567      C           VALUES FOR VARIABLES IN INFLUENT OR REACTORS
568      C          THE SUFFIX 'R' AFTER A SYMBOL INDICATES
569      C           VALUES FOR VARIABLES IN RECYCLE
570      C          THE SUFFIX 'P' AFTER A SYMBOL INDICATES VALUES
571      C           FOR VARIABLES CARRIED OVER TO PLOTTER ROUTINES
572      C          THE SUFFIX 'MAV' AFTER A SYMBOL INDICATES DAILY AVERAGE
573      C           VALUES OF VARIABLES FOR PROCESS
574      C
575      C         BALC = PERCENTAGE COD RECOVERY
```

```
576      C         TCODI = TOTAL COD MASS INPUT
577      C         TCODO = TOTAL COD MASS OUTPUT
578      C         TWCOD = TOTAL COD MASS IN WASTE FLOWS FROM REACTORS
579      C          WCOD = COD MASS IN WASTE FLOW FROM REACTOR
580      C          ECOD = TOTAL COD MASS IN EFFLUENT
581      C          BALN = PERCENTAGE NITROGEN RECOVERY
582      C          TNTI = TOTAL NITROGEN MASS INPUT
583      C          TNTO = TOTAL NITROGEN MASS OUTPUT
584      C           TWN = TOTAL NITROGEN MASS IN WASTE FLOWS FROM REACTORS
585      C            WN = NITROGEN MASS IN WASTE FLOW FROM REACTOR
586      C            EN = TOTAL NITROGEN MASS IN EFFLUENT
587      C
588            DT=1./D
589            DDT=1./DD
590            RDT=DDT/DT
591      C*********************************************************************
592            CALL DSTRCY(CRIT,VP,XVSS,NR,LINI,LSRI,LARI,LARO,LBRI,LBRO,
593           1QSR,QAR,QBR,SR,AR,BR,DT,DDT,RDT,NLL)
594      C*********************************************************************
595      C
596      C              RELATE STEP INTERVALS TO THE TIME BASE
597      C              --------------------------------------
598      C
599            II=0
600            KN=1440/D
601            KH1=KH+1
602            DO 27 I=1,NL,1
603            JE=I-1
604            IF(JE.EQ.0) GO TO 3
605            KO(I)=KO(I-1)+KN
606            GO TO 4
607          3 KO(I)=KOM
608          4 II=II+1
609            IF (II.EQ.KH1) KO(I)=KO(I)+40
610            IF (II.EQ.KH1) II=1
611            IF (KO(I).EQ.2400) KO(I)=0
612            IF(KO(I).EQ.ICSD) IC=I-1
613            IF(KOM.EQ.ICSD) IC=1
614            IF(KO(I).EQ.ISSD) IS=I
615         27 CONTINUE
616            HK=IS-IC
617            DO 9 J=1,NR,1
618            DO 29 I=1,NL,1
619            WQ(J,I)=0.0
620         29 CONTINUE
621            IF(LRSD(J).EQ.0) GO TO 32
622            DO 28 I=IC,IS,1
623            WQ(J,I)=VP/RS*D/HK*1.0/NRSD/DSFCTR(J)
624         28 CONTINUE
625         32 DO 48 I=1,NL,1
626            Q(J+1,I)=Q(J,I)-WQ(J,I)
627            IF(Q(J+1,I).GT.0.00) GO TO 48
628            Q(J+1,I)=0.00
629            WQ(J,I)=Q(J,I)
630         48 CONTINUE
631          9 CONTINUE
632      C
633      C              SET INITIAL CONDITIONS
634      C              ----------------------
635      C
636            DUM=(1.0+SR)/SR
637            DO 7  J=1,NR,1
638            DO 7 I=1,NL,1
639            SBP(J,I)=SBPSS*DSFCTR(J)
```

```
640           SBS(J,I)=SBSSS
641           XS(J,I)=XSSS*DSFCTR(J)
642           XA(J,I)=XASS*DSFCTR(J)
643           XE(J,I)=XESS*DSFCTR(J)
644           XI(J,I)=XISS*DSFCTR(J)
645           XV(J,I)=XVSS*DSFCTR(J)
646           SU(J,I)=SUSS
647           NU(J,I)=NUSS
648           NON(J,I)=NONSS
649           NH3(J,I)=NH3SS
650           XN(J,I)=XNSS*DSFCTR(J)
651           NO3(J,I)=NO3SS
652           ALK(J,I)=ALKSS
653           IF(J.NE.NR) GO TO 7
654           SBPR(I)=SBP(J,I)*DUM
655           XSR(I)=XS(J,I)*DUM
656           XAR(I)=XA(J,I)*DUM
657           XER(I)=XE(J,I)*DUM
658           XIR(I)=XI(J,I)*DUM
659           XNR(I)=XN(J,I)*DUM
660         7 CONTINUE
661           DO 10 J=1,NR,1
662           DO 10 I=1,NL
663           STOSBP(J,I)=SBP(J,I)
664           STNO3(J,I)=NO3(J,I)
665           STOXV(J,I)=XV(J,I)
666           STOXS(J,I)=XS(J,I)
667           STOXN(J,I)=XN(J,I)
668        10 CONTINUE
669           DO 5 J=1,NR,1
670           WRITE(5,200) SBS(J,1),SBP(J,1),XS(J,1),XA(J,1),XE(J,1),XI(J,1),
671          1XV(J,1),XN(J,1),NO3(J,1),ALK(J,1),SU(J,1),NON(J,1),NH3(J,1)
672         5 CONTINUE
673       200 FORMAT(1H ,5X,13F7.2)
674           M=0
675       190 J=0
676       191 J=J+1
677           DO 199 I=1,D,1
678     C*****************************************************************
679           IF(NTDN(J,I).EQ.1) CALL AROMOD(D,DT,J,I,FR,FBS,FCS,KVT,KMPT,KSPT,
680          1KMST,KSST,P,NR,YH,BHT,F,KRT,FOE,FN,FOS,FNS,NJ,DDT,UMT,YN,KNT,
681          2RDT,BNT,FACT,LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR)
682     C*****************************************************************
683           IF(NTDN(J,I).EQ.0) CALL ANOMOD(D,DT,J,I,FR,FBS,FCS,KVT,KMPT,KSPT,
684          1KMST,KSST,P,NR,YH,BHT,F,KRT,FOE,FN,FOS,FNS,NJ,DDT,UMT,YN,KNT,
685          2RDT,BNT,FACT,LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR)
686     C*****************************************************************
687       199 CONTINUE
688           IF(J.EQ.NR) GO TO 192
689           GO TO 191
690       192 CONTINUE
691     C*****************************************************************
692           CALL SETLCY(NL,J,QSR)
693     C*****************************************************************
694           DO 18 J=1,NR,1
695           DO 18 I=1,NL
696           IF(DABS(SBP(J,I)-STOSBP(J,I)).GE.CRISBP) GO TO 14
697           IF(DABS(NO3(J,I)-STNO3(J,I)).GE.CRINO3) GO TO 14
698           IF(DABS(XV(J,I)-STOXV(J,I)).GE.CRITXV) GO TO 14
699           IF(DABS(XS(J,I)-STOXS(J,I)).GE.CRITXS) GO TO 14
700           IF(DABS(XN(J,I)-STOXN(J,I)).GE.CRITXN) GO TO 14
701        18 CONTINUE
702           GO TO 15
703        14 M=M+1
```

```
      IF (M.GE.200) GO TO 15
      DO 16 J=1,NR,1
      DO 16 I=1,NL
      STOSBP(J,I)=SBP(J,I)
      STNO3(J,I)=NO3(J,I)
      STOXV(J,I)=XV(J,I)
      STOXS(J,I)=XS(J,I)
      STOXN(J,I)=XN(J,I)
   16 CONTINUE
      DO 6 J=1,NR,1
      SBP(J,1)=SBP(J,NL)
      SBS(J,1)=SBS(J,NL)
      XS(J,1)=XS(J,NL)
      XA(J,1)=XA(J,NL)
      XE(J,1)=XE(J,NL)
      XI(J,1)=XI(J,NL)
      SU(J,1)=SU(J,NL)
      NU(J,1)=NU(J,NL)
      NON(J,1)=NON(J,NL)
      NH3(J,1)=NH3(J,NL)
      XN(J,1)=XN(J,NL)
      NO3(J,1)=NO3(J,NL)
      ALK(J,1)=ALK(J,NL)
      XV(J,1)=XV(J,NL)
    6 CONTINUE
      GO TO 190
   15 CONTINUE
      DO 26 J=1,NR,1
      DO 26 I=1,NL
      JA=I-1
      IF (JA.EQ.0) JA=D
      JB=I+1
      IF (JB.EQ.NLL) JB=2
      JD=I
      IF(JD.EQ.NL) JD=1
      RXS(J,I)=(XS(J,JB)-XS(J,JA))/(DT*2.0)
      ST(J,I)=SU(J,I)+SBS(J,I)
      NT(J,I)=NON(J,I)+NU(J,I)+NH3(J,I)
      OC(J,I)=(1.0-P*YH)*SYNTH(J,JD)/(DT*24.0)
      ANPOT(J,I)=ANPOT(J,JD)/(DT*24.0)
      ON(J,I)=4.57*NIT(J,JD)/(DT*24.0)
      OT(J,I)=OC(J,I)+ON(J,I)
      AMON(J,I)=AMON(J,JD)/(DT*24.0)
   26 CONTINUE
C
C     CALCULATION OF AVERAGE RESULTS FROM DYNAMIC MODEL
C     -------------------------------------------------
C         EXAMPLE:  XVAV = AVERAGE XV
C
      TRN=0.0
      SUMXVT=0.0
      SUMWST=0.0
      SUMXAM=0.0
      SUMXEM=0.0
      SUMXIM=0.0
      SUMXSM=0.0
      SUMXNM=0.0
      SUMODM=0.0
      SMAPTM=0.0
      APTMNR=0.0
      RNO3AV=0.0
      SUMOCM=0.0
      SUMONM=0.0
      SUMOTM=0.0
```

```
768            SUMAMM=0.0
769            SUNSWM=0.0
770            TWCOD=0.0
771            TWN=0.0
772            EN=0.0
773            EALK=0.0
774            ECOD=0.0
775            DO 31 J=2,NRR,1
776            SUMQ=0.0
777            DO 30 I=1,D,1
778         30 SUMQ=SUMQ+Q(J,I)
779         31 QAV(J)=SUMQ/D
780            DO 22 J=1,NR,1
781            SUMWS=0.0
782            SUMNSW=0.0
783            SUMNU=0.0
784            SUMXA=0.0
785            SUMXE=0.0
786            SUMXI=0.0
787            SUMSBP=0.0
788            SUMSBS=0.0
789            SUMXV=0.0
790            SUMXS=0.0
791            SUMXN=0.0
792            SUMOC=0.0
793            SUMOD=0.0
794            SUMAPT=0.0
795            SUMON=0.0
796            SUMSU=0.0
797            SUMRXS=0.0
798            SUMNON=0.0
799            SUMNH3=0.0
800            SUMNT=0.0
801            SUMNO3=0.0
802            SUMALK=0.0
803            SUMOT=0.0
804            SUMAM=0.0
805            WCOD=0.0
806            WN=0.0
807            WALK=0.0
808            TWALK=0.0
809            DO 21 I=1,D
810            SUMWS=SUMWS+XV(J,I)*WQ(J,I)*DT
811            SUMNSW=SUMNSW+(FN*(XA(J,I)+XE(J,I)+XI(J,I))+FNS*XS(J,I))
812           1*WQ(J,I)*DT
813            IF(J.NE.NR) GO TO 11
814            ECOD=ECOD+Q(J+1,I)*ST(J,I)*DT
815            EN=EN+Q(J+1,I)*(NT(J,I)+NO3(J,I))*DT
816            EALK=EALK+Q(J+1,I)*ALK(J,I)*DT
817         11 SUMNU=SUMNU+NU(J,I)
818            SUMXA=SUMXA+XA(J,I)
819            SUMXE=SUMXE+XE(J,I)
820            SUMXI=SUMXI+XI(J,I)
821            SUMSBP=SUMSBP+SBP(J,I)
822            SUMSBS=SUMSBS+SBS(J,I)
823            SUMXV=SUMXV+XV(J,I)
824            SUMXN=SUMXN+XN(J,I)
825            SUMXS=SUMXS+XS(J,I)
826            SUMOC=SUMOC+OC(J,I)
827            SUMAPT=SUMAPT+ANPOT(J,I)
828            IF(NTDN(J,I).EQ.1) GO TO 12
829            SUMOD=SUMOD+OC(J,I)
830         12 SUMON=SUMON+ON(J,I)
831            SUMSU=SUMSU+SU(J,I)
```

```
832           SUMRXS=SUMRXS+RXS(J,I)
833           SUMNO3=SUMNO3+NO3(J,I)
834           SUMALK=SUMALK+ALK(J,I)
835           SUMNON=SUMNON+NON(J,I)
836           SUMNH3=SUMNH3+NH3(J,I)
837           SUMNT=SUMNT+NT(J,I)
838           WCOD=WCOD+WQ(J,I)*(ST(J,I)+SBP(J,I))*DT
839           WN=WN+WQ(J,I)*(NT(J,I)+NO3(J,I))*DT
840           WALK=WALK+WQ(J,I)*ALK(J,I)*DT
841           SUMOT=SUMOT+OT(J,I)
842           SUMAM=SUMAM+AMON(J,I)
843        21 CONTINUE
844           NUAV(J)=SUMNU/D
845           XAAV(J)=SUMXA/D
846           XEAV(J)=SUMXE/D
847           XIAV(J)=SUMXI/D
848           SBPAV(J)=SUMSBP/D
849           SBSAV(J)=SUMSBS/D
850           XVAV(J)=SUMXV/D
851           XSAV(J)=SUMXS/D
852           XNAV(J)=SUMXN/D
853           OCAV(J)=SUMOC/D
854           ODAV(J)=SUMOD/D
855           APTAV(J)=SUMAPT/D
856           APTNR(J)=APTAV(J)*24.0*V(J)/QAV(1)
857           RNO3(J)=ODAV(J)*24.0*V(J)/(QAV(1)*2.85)
858           ONAV(J)=SUMON/D
859           SUAV(J)=SUMSU/D
860           RXSAV(J)=SUMRXS/D
861           STAV(J)=SUAV(J)+SBSAV(J)
862           NSWAV(J)=SUMNSW/QAV(1)
863           SUNSWM=SUNSWM+NSWAV(J)
864           OTAV(J)=SUMOT/D
865           AMAV(J)=SUMAM/D
866           NO3AV(J)=SUMNO3/D
867           ALKAV(J)=SUMALK/D
868           NONAV(J)=SUMNON/D
869           NH3AV(J)=SUMNH3/D
870           NTAV(J)=SUMNT/D
871           SUMWST=SUMWST+SUMWS
872           SUMXVT=SUMXVT+XVAV(J)*V(J)
873           SUMXAM=SUMXAM+XAAV(J)*V(J)
874           SUMXEM=SUMXEM+XEAV(J)*V(J)
875           SUMXIM=SUMXIM+XIAV(J)*V(J)
876           SUMXSM=SUMXSM+XSAV(J)*V(J)
877           SUMXNM=SUMXNM+XNAV(J)*V(J)
878           SUMODM=SUMODM+ODAV(J)*V(J)
879           SMAPTM=SMAPTM+APTAV(J)*V(J)
880           APTMNR=APTMNR+APTNR(J)
881           RNO3AV=RNO3AV+RNO3(J)
882           SUMOCM=SUMOCM+OCAV(J)*V(J)
883           SUMONM=SUMONM+ONAV(J)*V(J)
884           SUMOTM=SUMOTM+OTAV(J)*V(J)
885           SUMAMM=SUMAMM+AMAV(J)*V(J)
886           I=NLL
887           Q(J,I)=QAV(J)
888     C*****************************************************************
889           CALL DUMVCY(J,I,DUMIF,DUMS,DUMA,DUMB,DUMIR,DUMO,
890          1LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR,
891          1DT,DDT,RDT)
892     C*****************************************************************
893           RA(J)=24.0*DDT/DUMO
894           RN(J)=V(J)/QAV(J)*24.0
895           TWCOD=TWCOD+WCOD
```

```
      TWN=TWN+WN
      TWALK=TWALK+WALK
      TRN=TRN+RN(J)
   22 CONTINUE
      RSAV=SUMXVT/SUMWST
      XAMAV=SUMXAM/VP
      XEMAV=SUMXEM/VP
      XIMAV=SUMXIM/VP
      XSMAV=SUMXSM/VP
      XVMAV=SUMXVT/VP
      XNMAV=SUMXNM/VP
      ODMAV=SUMODM/VP
      APTMAV=SMAPTM/VP
      OCMAV=SUMOCM/VP
      ONMAV=SUMONM/VP
      OTMAV=SUMOTM/VP
      AMMAV=SUMAMM/VP
C
C      CHECK MASS BALANCES ON COD , NITROGEN AND ALKALINITY
C      ----------------------------------------
C  1.  COD
C  -------
      TCODI=STQAV
      TCODO=P*SUMWST+SUMOCM*24.0+TWCOD+ECOD
      BALC=TCODO*100.0/TCODI
C  2.  NITROGEN
C  ------------
      TNTI=NTQAV
      TNTO=SUNSWM*QAV(1)+TWN+EN+SUMODM*24/2.85
      BALN=TNTO*100.0/TNTI
C  3.  ALKALINITY
C  --------------
      TALKI=ALKQAV
      TALKO=TWALK+EALK
     &+3.57*24.0*(2.0*SUMONM/4.57-SUMODM/2.86-SUMAMM)
      BALALK=TALKO/TALKI*100.0
C
C      OUTPUT AND FORMAT STATEMENTS
C      ----------------------------
C
      IF(RESULT.EQ.2) GO TO 126
      WRITE(5,201)TEMP,PH,YH,BHT,KVT,YN,THEN,F,FBS,FN,KNT,PHIN,
     1THEE,P,FOE,UMT,BNT,FOS,KRT,KSPT,THEZ,KMPT,THEA,THES,
     2KMST,KSST,FR,FNS,RSM,RS,RSA
  201 FORMAT(1H1,20X,22(1H*),/,1H ,20X,22(1H*),/,
     11H ,20X,22(1H*),/,
     11H0,10X,'KINETIC CONSTANTS',/,1H ,10X,17(1H-),/,
     21H ,5X,'PROCESS OPERATING TEMPERATURE=',F5.1,1X,'DEG. C',/,
     31H ,28X,'AND PH=',F5.2,/,1H0,5X,'HETEROTROPHS',28X,'AUTOTROPHS',/,
     41H ,5X,12(1H-),28X,10(1H-),/,1H ,6X,'YH=',F5.3,4X,'BH=',F5.3,4X,
     5'KV=',F5.3,8X,'YN=',F5.3,6X,'THEN=',F5.3,/,1H ,7X,'F=',F5.3,3X,
     6'FBS=',F5.3,4X,'FN=',F5.3,8X,'KN=',F5.2,6X,'PHIN=',F5.3,/,
     75X,'THEE=',F5.3,5X,'P=',F5.3,3X,'FOE=',F5.3,8X,'UM=',F5.3,
     28X,'BN=',F5.3,/,
     86X,'FOS=',F5.3,4X,'KR=',F5.3,3X,'KSP=',F5.3,6X,'THEZ=',F5.3,/,
     16X,'KMP=',F5.3,2X,'THEA=',F5.3,2X,'THES=',F5.3,/,
     26X,'KMS=',F5.2,3X,'KSS=',F5.1,/,
     27X,'FR=',F5.3,3X,'FNS=',F5.3,/,
     91H0,5X,'MINIMUM SLUDGE AGE FOR NITRIFICATION=',F5.2,1X,'DAYS',/,
     11H ,5X,'OPERATING SLUDGE AGE OF PROCESS=',F5.2,1X,'DAYS',/,
     11H ,5X,'AEROBIC SLUDGE AGE OF PROCESS=',F5.2,1X,'DAYS')
      WRITE(5,202)FUP,FUS,SN,UN,QAV(1),STQAV,NTQAV,STIAV,SBIAV,SUIAV,
     1XIIAV,NTIAV,NH3IAV,NONIAV,NUIAV,NO3IAV,ALKIAV
  202 FORMAT(1H0,10X,'AVERAGE COMPOSITION OF SEWAGE',/,
```

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     11H ,10X,29(1H-),/,1H0,5X,'SOLID INERT FRACTION OF INFLUENT COD=',
     2F5.3,/,1H ,5X,'SOLUBLE INERT FRACTION OF INFLUENT COD=',F5.3,/,
     31H ,5X,'AMMONIA TO TKN FRACTION=',F5.3,/,
     41H ,5X,'INERT TKN FRACTION=',F5.3,/,1H0,4X,'QAV=',F9.5,
     15X,'STQAV=',E13.5,5X,'NTQAV=',E13.5,/,
     51H ,5X,'STI=',F7.2,5X,'SBI=',F7.2,4X,'SUI=',F6.2,
     64X,'XII=',F6.2,/,1H ,5X,'NTI=',F6.2,4X,'NH3I=',F6.2,
     74X,'NONI=',F5.2,5X,'NUI=',F5.2,5X,'NO3I=',F5.2,/,
     &4X,'ALKI=',F7.2)
      IF(TYPE.EQ.1) GO TO 122
      IF(TYPE.EQ.2) GO TO 123
      IF(TYPE.EQ.3) GO TO 122
  122 WRITE(5,205)VARQ,VARSTI,VARNTI,VNO3I,VALKI,VARSTL,VARNTL,VRNO3L,
     &VRALKL
  205 FORMAT(1H0,10X,'SINE WAVE INFLUENT FLOW AND FEED PATTERN',/,
     11H ,10X,40(1H-),/,
     41H0,10X,'AMPLITUDE OF FLOW WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
     51H ,10X,'AMPLITUDE OF COD WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
     61H ,10X,'AMPLITUDE OF TKN WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
     71H ,10X,'AMPLITUDE OF NO3 WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
     71H ,10X,'AMPLITUDE OF ALK WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
     81H ,10X,'AMPLITUDE OF COD LOAD WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
     81H ,10X,'AMPLITUDE OF TKN LOAD WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
     81H ,10X,'AMPLITUDE OF NO3 LOAD WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
     81H ,10X,'AMPLITUDE OF ALK LOAD WAVE=',F5.2,4X,'(FRAC OF AVE)')
      WRITE(5,204) NR,LINI,LSRI,LARO,LARI,LBRO,LBRI,SR,AR,BR
  204 FORMAT(1H0,10X,'PROCESS CONFIGURATION DATA',/,1H ,5X,26(1H-),/,
     11H0,5X,'NUMBER OF TANKS IN SERIES',I2,/,
     11H ,5X,'INFLUENT FLOW INTO TANK',I2,/,
     11H ,5X,'S-RECYCLE FROM SETTLER TO TANK ',I2,/,
     11H ,5X,'A-RECYCLE FROM TANK',I2,1X,'INTO TANK',I2,/,
     11H ,5X,'B-RECYCLE FROM TANK',I2,1X,'INTO TANK',I2,/,
     11H ,5X,'S RECYCLE RATIO=',F4.1,/,
     11H ,5X,'A RECYCLE RATIO=',F4.1,/,
     11H ,5X,'B RECYCLE RATIO=',F4.1)
      GO TO 124
  123 WRITE(5,206)LFP,PQ,BQ,VF
  206 FORMAT(1H0,10X,'SQUARE WAVE INFLUENT FLOW AND FEED PATTERN',/,
     11H ,10X,42(1H-),/,
     11H ,10X,'LENGTH OF FEED PERIOD (HRS)=',F5.2,/,
     21H ,10X,'PEAK FLOW (L/D)=',F9.5,/,
     31H ,10X,'BASE FLOW (L/D)=',F9.5,/,
     41H ,10X,'VOLUME OF FEED PER DAY (LITRES)=' F9.5)
  124 WRITE(5,203) TRN,VP,SANOX,M,RSAV
  203 FORMAT(1H1,10X,21(1H-),/,1H ,10X,'DAILY AVERAGE RESULTS',/,
     11H ,10X,21(1H-),/,
     11H0,5X,'TOTAL HYDRAULIC RETENTION TIME=',F8.3,1X,'HOURS',/,
     11H ,5X,'TOTAL VOLUME=',E13.5,1X,'LITRES',/,
     11H ,5X,'ANOXIC FRACTION=',F6.2,1X,/,
     21H ,5X,'NO. OF DAYS TO REACH DYNAMIC STEADY STATE=',I3,/,
     21H ,5X,'SLUDGE AGE =',F5.2,1X,'DAYS')
      WRITE(5,244)TCODI,TCODO,BALC,TNTI,TNTO,BALN,TALKI,TALKO,BALALK
  244 FORMAT(1H0,10X,'MASS BALANCES ON COD AND NITROGEN',/,
     11H ,10X,33(1H-),/,
     21H0,5X,'TOTAL COD MASS INPUT=',1X,E13.6,1X,'(MG-COD/D)',/,
     21H ,5X,'TOTAL COD MASS OUTPUT=',1X,E13.6,1X,'(MG-COD/D)',/,
     31H ,5X,'PERCENTAGE COD RECOVERY=',1X,F7.3,1X,'(%)',/,
     21H ,5X,'TOTAL NITROGEN MASS INPUT=',1X,E13.6,1X,'(MG-N/D)',/,
     21H ,5X,'TOTAL NITROGEN MASS OUTPUT=',1X,E13.6,1X,'(MG-N/D)',/,
     31H ,5X,'PERCENTAGE NITROGEN RECOVERY=',1X,F7.3,1X,'(%)',/,
     21H ,5X,'TOTAL ALKALINITY MASS INPUT=',1X,E13.6,1X,'(CACO3/D)',/,
     21H ,5X,'TOTAL ALKALINITY MASS OUTPUT=',1X,E13.6,1X,'(CACO3/D)',/,
     31H ,5X,'PERCENTAGE ALKALINITY RECOVERY=',1X,F7.3,1X,'(%)')
      WRITE(5,300)
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```
1024          300 FORMAT(1H0,30X,'TANK  1',6X,'TANK  2',
1025             26X,'TANK  3',6X,'TANK  4',6X,'TANK  5',6X,'TANK  6',
1026             36X,'MEAN',/,1H ,30X,7(1H-),6X,7(1H-),6X,7(1H-),6X,7(1H-),
1027             46X,7(1H-),6X,7(1H-),6X,4(1H-))
1028              WRITE(5,327) (NAME(J),J=1,NR,1)
1029          327 FORMAT(1H ,23X,6A13)
1030              WRITE(5,328)
1031          328 FORMAT(1H ,30X,6(1H-),7X,6(1H-),7X,6(1H-),
1032             17X,6(1H-),7X,6(1H-),7X,6(1H-))
1033              WRITE(5,301) (XAAV(J),J=1,NR,1),XAMAV
1034              WRITE(5,302) (XSAV(J),J=1,NR,1),XSMAV
1035              WRITE(5,303) (XEAV(J),J=1,NR,1),XEMAV
1036              WRITE(5,304) (XIAV(J),J=1,NR,1),XIMAV
1037              WRITE(5,305) (XVAV(J),J=1,NR,1),XVMAV
1038              WRITE(5,319) (XNAV(J),J=1,NR,1),XNMAV
1039              WRITE(5,313) (ODAV(J),J=1,NR,1),ODMAV
1040              WRITE(5,314) (OCAV(J),J=1,NR,1),OCMAV
1041              WRITE(5,315) (ONAV(J),J=1,NR,1),ONMAV
1042              WRITE(5,316) (OTAV(J),J=1,NR,1),OTMAV
1043              WRITE(5,3160) (AMAV(J),J=1,NR,1),AMMAV
1044              WRITE(5,309) (NSWAV(J),J=1,NR,1),SUNSWM
1045              WRITE(5,321) (SBPAV(J),J=1,NR,1)
1046              WRITE(5,320) (SBSAV(J),J=1,NR,1)
1047              WRITE(5,324) (SUAV(J),J=1,NR,1)
1048              WRITE(5,311) (STAV(J),J=1,NR,1)
1049              WRITE(5,306) (NONAV(J),J=1,NR,1)
1050              WRITE(5,310) (NH3AV(J),J=1,NR,1)
1051              WRITE(5,323) (NUAV(J),J=1,NR,1)
1052              WRITE(5,312) (NTAV(J),J=1,NR,1)
1053              WRITE(5,307) (NO3AV(J),J=1,NR,1)
1054              WRITE(5,703) (ALKAV(J),J=1,NR,1)
1055              WRITE(5,308) (RNO3(J),J=1,NR,1),RNO3AV
1056              WRITE(5,326) (APTAV(J),J=1,NR,1),APTMAV
1057              WRITE(5,329) (APTNR(J),J=1,NR,1),APTMNR
1058              WRITE(5,3329) (FANOX(J),J=1,NR,1),SANOX
1059              WRITE(5,322) (V(J),J=1,NR,1)
1060              WRITE(5,325) (QAV(J),J=1,NRR,1)
1061              WRITE(5,317) (RA(J),J=1,NR,1)
1062              WRITE(5,318) (RN(J),J=1,NR,1)
1063           301 FORMAT(1H ,8X,'XA    (MG-VSS/L)',2X,7(E13.5))
1064           302 FORMAT(1H ,8X,'XS    (MG-VSS/L)',2X,7(E13.5))
1065           303 FORMAT(1H ,8X,'XE    (MG-VSS/L)',2X,7(E13.5))
1066           304 FORMAT(1H ,8X,'XI    (MG-VSS/L)',2X,7(E13.5))
1067           305 FORMAT(1H ,8X,'XV    (MG-VSS/L)',2X,7(E13.5))
1068           319 FORMAT(1H ,8X,'XN    (MG-VSS/L)',2X,7(E13.5))
1069           313 FORMAT(1H ,8X,'OD  (MG-O/L/HR)',2X,7(E13.5))
1070           314 FORMAT(1H ,8X,'OC  (MG-O/L/HR)',2X,7(E13.5))
1071           315 FORMAT(1H ,8X,'ON  (MG-O/L/HR)',2X,7(E13.5))
1072           316 FORMAT(1H ,8X,'OT  (MG-O/L/HR)',2X,7(E13.5))
1073          3160 FORMAT(1H ,8X,'AM  (MG-N/L/HR)',2X,7(E13.5))
1074           309 FORMAT(1H ,8X,'NSW  (MG-N/L/D)',2X,7(E13.5))
1075           321 FORMAT(1H ,8X,'SBP  (MG-COD/L)',2X,6(E13.5))
1076           320 FORMAT(1H ,8X,'SBS  (MG-COD/L)',2X,6(E13.5))
1077           324 FORMAT(1H ,8X,'SU   (MG-COD/L)',2X,6(E13.5))
1078           311 FORMAT(1H ,8X,'ST   (MG-COD/L)',2X,6(E13.5))
1079           306 FORMAT(1H ,8X,'NON    (MG-N/L)',2X,6(E13.5))
1080           310 FORMAT(1H ,8X,'NH3    (MG-N/L)',2X,6(E13.5))
1081           323 FORMAT(1H ,8X,'NU     (MG-N/L)',2X,6(E13.5))
1082           312 FORMAT(1H ,8X,'NT     (MG-N/L)',2X,6(E13.5))
1083           307 FORMAT(1H ,8X,'NO3    (MG-N/L)',2X,6(E13.5))
1084           703 FORMAT(1H ,8X,'ALK (MG-CACO3/L)',1X,6(E13.5))
1085           326 FORMAT(1H ,8X,'APT (MG-N/L/HR)',2X,7(E13.5))
1086           329 FORMAT(1H ,8X,'APTNR  (MG-N/L)',2X,7(E13.5))
1087          3329  FORMAT(1H ,8X,'ANOX. FRACTION ',2X,7(E13.5))
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1088        308 FORMAT(1H ,8X,'RNO3   (MG-N/L)',2X,7(E13.5))
1089        322 FORMAT(1H ,8X,'VOL    (LITRES)',2X,6(E13.5))
1090        325 FORMAT(1H ,8X,'FLOW      (L/D)',2X,7(E13.5))
1091        317 FORMAT(1H ,8X,'AHRT    (HOURS)',2X,6(E13.5))
1092        318 FORMAT(1H ,8X,'NHRT    (HOURS)',2X,6(E13.5))
1093            WRITE(CH,'(I1)')NR
1094            IMFT(10:10)=CH
1095            WRITE(5,399) (KO(I),STQ(I),NTQ(I),Q(1,I),SBI(I),STI(I),
1096           1NTI(I),SUI(I),NUI(I),XII(I),NH3I(I),NONI(I),I=1,NL,KH)
1097        399 FORMAT(1H1,10X,'DYNAMIC INPUTS',/,1H ,10X,14(1H-),/,
1098           11H ,2X,'TIME',2X,'COD LOAD',2X,'TKN LOAD',4X,'FLOW',7X,'SBI',7X,
1099           2'STI',7X,'NTI',7X,'SUI',7X,'NUI',7X,'XII',6X,'NH3I',6X,'NONI',/,
1100           31H ,2X,4(1H-),2X,8(1H-),3X,8(1H-),4X,4(1H-),7X,3(1H-),7X,3(1H-),
1101           47X,3(1H-),7X,3(1H-),7X,3(1H-),7X,3(1H-),6X,4(1H-),6X,4(1H-),/,
1102           5(1H ,2X,I4,11(E10.4)))
1103            WRITE(5,400)
1104        400 FORMAT(1H1,10X,21(1H-),/,1H ,10X,'DAILY DYNAMIC RESULTS',/,
1105           11H ,10X,21(1H-),/,
1106           11H0,20X,'TIME',5X,'TANK  1',6X,'TANK  2',
1107           26X,'TANK  3',6X,'TANK  4',6X,'TANK  5',6X,'TANK  6',/,
1108           31H ,20X,4(1H-),5X,7(1H-),6X,7(1H-),6X,7(1H-),6X,7(1H-),
1109           46X,7(1H-),6X,7(1H-))
1110            WRITE(5,401)
1111        401 FORMAT(1H0,3X,'XA    (MG-VSS/L)')
1112            WRITE(5,IMFT) (KO(I),(XA(J,I),J=1,NR,1),I=1,NL,KH)
1113            WRITE(5,402)
1114        402 FORMAT(1H0,3X,'XS    (MG-VSS/L)')
1115            WRITE(5,IMFT) (KO(I),(XS(J,I),J=1,NR,1),I=1,NL,KH)
1116            WRITE(5,403)
1117        403 FORMAT(1H0,3X,'XE    (MG-VSS/L)')
1118            WRITE(5,IMFT) (KO(I),(XE(J,I),J=1,NR,1),I=1,NL,KH)
1119            WRITE(5,404)
1120        404 FORMAT(1H0,3X,'XI    (MG-VSS/L)')
1121            WRITE(5,IMFT) (KO(I),(XI(J,I),J=1,NR,1),I=1,NL,KH)
1122            WRITE(5,405)
1123        405 FORMAT(1H0,3X,'XV    (MG-VSS/L)')
1124            WRITE(5,IMFT) (KO(I),(XV(J,I),J=1,NR,1),I=1,NL,KH)
1125            WRITE(5,419)
1126        419 FORMAT(1H0,3X,'XN    (MG-VSS/L)')
1127            WRITE(5,IMFT) (KO(I),(XN(J,I),J=1,NR,1),I=1,NL,KH)
1128            WRITE(5,407)
1129        407 FORMAT(1H0,3X,'OC   (MG-O/L/HR)')
1130            WRITE(5,IMFT) (KO(I),(OC(J,I),J=1,NR,1),I=1,NL,KH)
1131            WRITE(5,408)
1132        408 FORMAT(1H0,3X,'ON   (MG-O/L/HR)')
1133            WRITE(5,IMFT) (KO(I),(ON(J,I),J=1,NR,1),I=1,NL,KH)
1134            WRITE(5,409)
1135        409 FORMAT(1H0,3X,'OT   (MG-O/L/HR)')
1136            WRITE(5,IMFT) (KO(I),(OT(J,I),J=1,NR,1),I=1,NL,KH)
1137            WRITE(5,4090)
1138       4090  FORMAT(1H0,3X,'AM (MG-N/L/HR)')
1139            WRITE(5,IMFT) (KO(I),(AMON(J,I),J=1,NR,1),I=1,NL,KH)
1140            WRITE(5,417)
1141        417 FORMAT(1H0,3X,'WQ       (L/DAY)')
1142            WRITE(5,IMFT) (KO(I),(WQ(J,I),J=1,NR,1),I=1,NL,KH)
1143            WRITE(5,411)
1144        411 FORMAT(1H0,3X,'SBP   (MG-COD/L)')
1145            WRITE(5,IMFT) (KO(I),(SBP(J,I),J=1,NR,1),I=1,NL,KH)
1146            WRITE(5,418)
1147        418 FORMAT(1H0,3X,'SBS   (MG-COD/L)')
1148            WRITE(5,IMFT) (KO(I),(SBS(J,I),J=1,NR,1),I=1,NL,KH)
1149            WRITE(5,420)
1150        420 FORMAT(1H0,3X,'SU    (MG-COD/L)')
1151            WRITE(5,IMFT) (KO(I),(SU(J,I),J=1,NR,1),I=1,NL,KH)
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1152            WRITE(5,412)
1153          412 FORMAT(1H0,3X,'ST    (MG-COD/L)')
1154            WRITE(5,IMFT) (KO(I),(ST(J,I),J=1,NR,1),I=1,NL,KH)
1155            WRITE(5,413)
1156          413 FORMAT(1H0,3X,'NON     (MG-N/L)')
1157            WRITE(5,IMFT) (KO(I),(NON(J,I),J=1,NR,1),I=1,NL,KH)
1158            WRITE(5,421)
1159          421 FORMAT(1H0,3X,'NU      (MG-N/L)')
1160            WRITE(5,IMFT) (KO(I),(NU(J,I),J=1,NR,1),I=1,NL,KH)
1161            WRITE(5,415)
1162          415 FORMAT(1H0,3X,'NH3     (MG-N/L)')
1163            WRITE(5,IMFT) (KO(I),(NH3(J,I),J=1,NR,1),I=1,NL,KH)
1164            WRITE(5,414)
1165          414 FORMAT(1H0,3X,'NT      (MG-N/L)')
1166            WRITE(5,IMFT) (KO(I),(NT(J,I),J=1,NR,1),I=1,NL,KH)
1167            WRITE(5,422)
1168          422 FORMAT(1H0,3X,'APT (MG-N/L/HR)')
1169            WRITE(5,IMFT) (KO(I),(ANPOT(J,I),J=1,NR,1),I=1,NL,KH)
1170            WRITE(5,416)
1171          416 FORMAT(1H0,3X,'NO3     (MG-N/L)')
1172            WRITE(5,IMFT) (KO(I),(NO3(J,I),J=1,NR,1),I=1,NL,KH)
1173            WRITE(5,461)
1174          461 FORMAT(1H0,3X,'ALK     (MG-CACO3/L)')
1175            WRITE(5,IMFT) (KO(I),(ALK(J,I),J=1,NR,1),I=1,NL,KH)
1176            IF(RESULT.NE.0) GO TO 127
1177      C     ------------------------------------------------------------
1178      C       SET THE SOLUBLE EFFLUENT CONCENTRATIONS THAT ARE
1179      C
1180      C        TO BE WRITTEN TO THE PLOT FILE
1181      C     ------------------------------------------------------------
1182          126 ECOD=STAV(NR)
1183            ENT=NTAV(NR)
1184            ENH3=NH3AV(NR)
1185            ENO3=NO3AV(NR)
1186            EALK=ALKAV(NR)
1187      C
1188      C     ------------------------------------------------------------
1189      C       WRITE ALL THE PARAMETERS USED IN PLOTTING OF
1190      C
1191      C       SIMULATED RESPONSE TO THE PRINT FILE ( NO. 18)
1192      C     ------------------------------------------------------------
1193            WRITE(18,522)ECOD,ENT,ENH3,ENO3,EALK
1194            WRITE(18,522)KOM,D,INIT(1),ANOX(1),AROB(1),IFREQ,NDH
1195      522   FORMAT()
1196            WRITE(18,45)(OT(1,I),XV(1,I),ST(1,I),NT(1,I),NH3(1,I),NO3(1,I),
1197           &ALK(1,I),I=1,NDH)
1198            WRITE(18,522) START,END
1199      45    FORMAT(7E13.5)
1200            ENDFILE 18
1201      127   STOP
1202            END
```

```
1       C*****************************************************************
2             SUBROUTINE PARMOD(YH,FBS,RS,RSA,BHT,KVT,TRN,KMPT,KSPT,KMST,KSST,
3            1P,F,FN,FNS,KRT,KNT,BNT,UMT,YN,SR,AR,BR,FACT,FR,
4            2SBIAV,SUIAV,XIIAV,NUIAV,NONIAV,NTIAV,NO3IAV,STQAV,ALKIAV,
5            3XASS,XSSS,XESS,XISS,XVSS,XNSS,SBPSS,SBSSS,SUSS,
6            4NONSS,NH3SS,NO3SS,NUSS,ALKSS,VARNTL)
7       C*****************************************************************
8       C              THIS SUBROUTINE CALCULATES THE STEADY STATE
9       C               SOLUTION ( PARTICULAR INTEGRAL )
10      C*****************************************************************
11            PARAMETER NE=1
12            PARAMETER NEE=2
13            PARAMETER ND=241
14            PARAMETER NDD=242
15            REAL NUIAV,NONIAV,NTIAV,NO3IAV
16            REAL NH3MAX,NSW
17            COMMON/EXTC/SBS(NE,ND),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
18           1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,ND),NH3(NE,ND),
19           2NO3(NE,ND),SBP(NE,ND),ALK(NE,ND)
20            COMMON/BLOCKC/Q(NEE,NDD),V(NE),SBI(ND),SUI(ND),NIT(NE,ND),
21           1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),ALKI(ND),
22           2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(ND),SYNTH(NE,ND),QAV(NEE),
23           3ANPOT(NE,ND),AMON(NE,ND),DSFCTR(NE)
24            REAL KVT,KMPT,KSPT,KMST,KSST,KRT,KNT,KMPTEF
25            REAL NUI,NONI,NH3I,NO3I,NIT
26            REAL NU,NON,NH3,NO3
27            REAL NUSS,NONSS,NH3SS,NO3SS
28            KMPTEF=KMPT*(FACT*(1.0-RSA/RS)+RSA/RS)
29            XA0=YH*RS/(TRN*(1.+BHT*RS*(1.-P*YH*(1.-F))))*SBIAV
30            SBSI=FBS*SBIAV
31            SBPI=SBIAV-SBSI
32            SBS0=0.0
33            SBP0=0.0
34            XS0=0.0
35            DO 15 KLM=1,100,1
36            C6=SBSI-KSST-TRN*KMST*XA0
37            SBSS=(C6+(C6*C6+4.0*KSST*SBSI)**0.5)/2.0
38            SBPSS=(SBPI/TRN+(1.0-F)*BHT*P*XA0)/(1.0/RS+KVT*XA0*(FR-XS0/XA0))
39            C1=-(P/RS+KVT*SBPSS)/XA0
40            C2=KVT*SBPSS*(P-KSPT)/P-KMPTEF-KSPT/RS
41            C3=KVT*SBPSS*KSPT*XA0/P
42            XSSS=(-C2-(C2*C2-4.0*C1*C3)**0.5)/(2.0*C1)
43            SB=TRN/RS*(XSSS*P+SBPSS)+SBSS
44            SYNEF=SB/SBIAV
45            XASS=YH*(1.0-SYNEF)*SBIAV*RS/
46           &(TRN*(1.0+BHT*RS*(1.0-P*YH*(1.0-F))))
47            IF(XASS.LT.0.0)GO TO 55
48            IF(XSSS.GE.(FR*XASS)) XSSS=FR*XASS
49      4     DIF=(XS0-XSSS)**2.0
50            DIF2=(SBP0-SBPSS)**2.0
51            IF(DIF.LT.0.01.AND.DIF2.LT.0.01) GO TO 6
52            SBS0=SBSS
53            SBP0=SBPSS
54            XS0=XSSS
55            XA0=XASS
56            IF (KLM.EQ.100) GO TO 55
57      15    CONTINUE
58      6     XESS=F*BHT*XASS*RS
59            XISS=XIIAV*RS/TRN
60            XVSS=XASS+XSSS+XESS+XISS
61            SUSS=SUIAV
62            NUSS=NUIAV
63            WRITE(5,25) RS,SBSSS,SBPSS,XSSS,SB,XASS,XESS,XISS,XVSS,SYNEF,KLM
```

```
64      25    FORMAT(1H, 5X,10F11.3,I4)
65            NSW=(FN*(XASS+XESS+XISS)+FNS*XSSS)*TRN/RS
66            NONSS=(NONIAV+TRN*((1.0-F)*FN*BHT*XASS-FNS*XSSS))/
67           1(1.0+KRT*XASS*TRN)
68            NH3MAX=NTIAV-NSW-NUSS-NONSS
69            NH3SS=KNT*(BNT+1.0/RS)/(UMT*RSA/RS-BNT-1.0/RS)*(1+VARNTL/TRN)
70            IF(NH3SS.GT.NH3MAX) NH3SS=NH3MAX
71            IF(NH3SS.LE.0.0) NH3SS=NH3MAX
72            XNSS=YN*(NH3MAX-NH3SS)*RS/(TRN*(1.0+BNT*RS))
73            NO3SS=NO3IAV+NH3MAX-NH3SS
74            IF(RS.EQ.RSA) GO TO 36
75            DENCON=((1-P*YH)/2.86)*KMPT*FACT*P*XSSS/(XSSS*P+KSPT*XASS)
76            CR=YH*RS/(1.0+BHT*RS*(1.0-P*YH*(1.0-F)))
77            DENCAP=(FBS*(1.0-P*YH)/2.86+DENCON*(1.0-RSA/RS)*CR)*SBIAV
78            NO3SS=NO3SS-DENCAP
79            IF(NO3SS.LT.0.0) NO3SS=0.0
80            ALKSS=ALKIAV-7.14*(NH3MAX-NH3SS)
81           &+3.57*(NONIAV-NONSS-NSW+DENCAP)
82            GO TO 35
83      55    WRITE(5,65)
84      65    FORMAT(1H ,10X,'NO SOLUTION AFTER 100 ITERATIONS OR XA.LT.0.0')
85         36 ALKSS=ALKIAV-7.14*(NH3MAX-NH3SS)
86           &+3.57*(NONIAV-NONSS-NSW)
87      35    CONTINUE
88            RETURN
89            END
```

```
      C*****************************************************************
            SUBROUTINE AROMOD(D,DT,J,I,FR,FBS,FCS,KVT,KMPT,KSPT,KMST,KSST,
           1P,NR,YH,BHT,F,KRT,FOE,FN,FOS,FNS,NJ,DDT,UMT,YN,KNT,RDT,BNT,
           2FACT,LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR)
      C*****************************************************************
      C             THIS SUBROUTINE CALCULATES THE DYNAMIC RESPONSE OF THE
      C              FIRST REACTOR IN A SERIES UNDER AEROBIC CONDITIONS
      C*****************************************************************
            PARAMETER NE=1
            PARAMETER NEE=2
            PARAMETER ND=241
            PARAMETER NDD=242
            INTEGER D
            DOUBLE PRECISION DT,DDT,RDT
            COMMON/EXTC/SBS(NE,ND),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
           1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,ND),NH3(NE,ND),
           2NO3(NE,ND),SBP(NE,ND),ALK(NE,ND)
            COMMON/BLOCKC/Q(NEE,NDD),V(NE),SBI(ND),SUI(ND),NIT(NE,ND),
           1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),ALKI(ND),
           2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(ND),SYNTH(NE,ND),QAV(NEE),
           3ANPOT(NE,ND),AMON(NE,ND),DSFCTR(NE)
            REAL KVT,KMPT,KSPT,KMST,KSST,KRT,KNT
            REAL NUI,NONI,NH3I,NO3I,NIT
            REAL NU,NON,NH3,NO3
            REAL NH3A,NH3S,NH3T,NH3B,NH3K,NITT,NNIT,NO3A,NO3S,NO3T,NO3B,NO3K
      C*****************************************************************
            CALL DUMVCY(J,I,DUMIF,DUMS,DUMA,DUMB,DUMIR,DUMO,
           1LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR,
           1DT,DDT,RDT)
      C*****************************************************************
            K=J-1
            IF(K.EQ.0) K=1
            SCER=P*(1.0-F)*BHT*XA(J,I)*DDT
            SCERN=FN*SCER/P
            CVNON=KRT*XA(J,I)*NON(J,I)*DDT
            SCVOD=KMPT*XS(J,I)/(KSPT*XA(J,I)+XS(J,I)*P)*XA(J,I)*DDT
            SCVO=0.00
            SCIS=0.00
            NNIT=0.00
            SBST=SBS(J,I)
            DFSBSS=(SBS(NR,I+1)-SBS(NR,I))/NJ
            DFSBSA=(SBS(LARO,I+1)-SBS(LARO,I))/NJ
            DFSBSB=(SBS(LBRO,I+1)-SBS(LBRO,I))/NJ
            DFSBSK=(SBS(K,I+1)-SBS(K,I))/NJ
            NH3T=NH3(J,I)
            DFNH3S=(NH3(NR,I+1)-NH3(NR,I))/NJ
            DFNH3A=(NH3(LARO,I+1)-NH3(LARO,I))/NJ
            DFNH3B=(NH3(LBRO,I+1)-NH3(LBRO,I))/NJ
            DFNH3K=(NH3(K,I+1)-NH3(K,I))/NJ
            NO3T=NO3(J,I)
            DFNO3S=(NO3(NR,I+1)-NO3(NR,I))/NJ
            DFNO3A=(NO3(LARO,I+1)-NO3(LARO,I))/NJ
            DFNO3B=(NO3(LBRO,I+1)-NO3(LBRO,I))/NJ
            DFNO3K=(NO3(K,I+1)-NO3(K,I))/NJ
            XNT=XN(J,I)
            DFXNS=(XNR(I+1)-XNR(I))/NJ
            DFXNA=(XN(LARO,I+1)-XN(LARO,I))/NJ
            DFXNB=(XN(LBRO,I+1)-XN(LBRO,I))/NJ
            DFXNK=(XN(K,I+1)-XN(K,I))/NJ
            DO 12 IJ=1,NJ,1
            SCVOT=SCVOD
            SCIST=KMST*SBST/(KSST+SBST)*XA(J,I)*DDT
            SBSS=SBS(NR,I)+(IJ-1)*DFSBSS
```

```
64              SBSA=SBS(LARO,I)+(IJ-1)*DFSBSA
65              SBSB=SBS(LBRO,I)+(IJ-1)*DFSBSB
66              SBSK=SBS(K,I)+(IJ-1)*DFSBSK
67              SBST=SBST+DUMIF*FBS*SBI(I)-SCIST+FCS*SCER
68             1+DUMS*SBSS+DUMA*SBSA-DUMO*SBST
69             1+DUMB*SBSB+DUMIR*SBSK
70              IF(SBST.LT.0.00) SBST=0.00
71              SCVO=SCVO+SCVOT
72              SCIS=SCIS+SCIST
73              SYNTHT=SCVOT*P+SCIST
74              NITT=(UMT/YN)*NH3T/(KNT+NH3T)*XNT*DDT
75              NNIT=NNIT+NITT
76              NH3S=NH3(NR,I)+(IJ-1)*DFNH3S
77              NH3A=NH3(LARO,I)+(IJ-1)*DFNH3A
78              NH3B=NH3(LBRO,I)+(IJ-1)*DFNH3B
79              NH3K=NH3(K,I)+(IJ-1)*DFNH3K
80              NO3S=NO3(NR,I)+(IJ-1)*DFNO3S
81              NO3A=NO3(LARO,I)+(IJ-1)*DFNO3A
82              NO3B=NO3(LBRO,I)+(IJ-1)*DFNO3B
83              NO3K=NO3(K,I)+(IJ-1)*DFNO3K
84              TNH3T=NH3T+DUMIF*NH3I(I)+CVNON-NITT
85             1+DUMS*NH3S+DUMA*NH3A-DUMO*NH3T
86             1+DUMB*NH3B+DUMIR*NH3K
87             1+(1.0-FOE)*SCERN-(1.0-FOS)*FN*YH*SYNTHT
88              IF(TNH3T.GT.0.0) GO TO 43
89              NH3T=0.0
90              NO3T=NO3T+DUMIF*NO3I(I)+NITT+TNH3T
91             1+DUMS*NO3S+DUMA*NO3A-DUMO*NO3T
92             1+DUMB*NO3B+DUMIR*NO3K
93              GO TO 44
94             43 NH3T=TNH3T
95                NO3T=NO3T+DUMIF*NO3I(I)+NITT
96               1+DUMS*NO3S+DUMA*NO3A-DUMO*NO3T
97               1+DUMB*NO3B+DUMIR*NO3K
98             44 XNS=XNR(I)+(IJ-1)*DFXNS
99                XNA=XN(LARO,I)+(IJ-1)*DFXNA
100               XNB=XN(LBRO,I)+(IJ-1)*DFXNB
101               XNK=XN(K,I)+(IJ-1)*DFXNK
102               XNT=XNT+YN*NITT-BNT*XNT*DDT
103              1+DUMS*XNS+DUMA*XNA-DUMO*XNT
104              1+DUMB*XNB+DUMIR*XNK
105            12 CONTINUE
106               SYNTH(J,I)=SCVO*P+SCIS
107               NIT(J,I)=NNIT
108               ANPOT(J,I)=0.00
109               SBS(J,I+1)=SBST
110               NH3(J,I+1)=NH3T
111               NO3(J,I+1)=NO3T
112               XN(J,I+1)=XNT
113               DUMIF=DUMIF/RDT
114               DUMIR=DUMIR/RDT
115               DUMA=DUMA/RDT
116               DUMB=DUMB/RDT
117               DUMS=DUMS/RDT
118               DUMO=DUMO/RDT
119               BRAK=FR-(XS(J,I)/(XA(J,I)))
120               IF(BRAK.GT.0.00) GO TO 40
121               BRAK=0.00
122               XS(J,I)=FR*(XA(J,I))
123            40 XV(J,I)=XS(J,I)+XA(J,I)+XE(J,I)+XI(J,I)
124               SCIP=DT*KVT*BRAK*SBP(J,I)*XA(J,I)
125               SBP(J,I+1)=SBP(J,I)+DUMIF*(1.0-FBS)*SBI(I)-SCIP
126              1+DUMS*SBPR(I)+DUMA*SBP(LARO,I)-DUMO*SBP(J,I)
127              1+DUMB*SBP(LBRO,I)+DUMIR*SBP(K,I)
```

```
128           2+(1.0-FCS)*SCER/RDT
129            IF(SBP(J,I+1).LT.0.0) SBP(J,I+1)=0.0
130            XS(J,I+1)=XS(J,I)+SCIP/P-SCVO
131           1+DUMS*XSR(I)+DUMA*XS(LARO,I)-DUMO*XS(J,I)
132           1+DUMB*XS(LBRO,I)+DUMIR*XS(K,I)
133            IF(XS(J,I+1).LT.0.0) XS(J,I+1)=0.0
134            SU(J,I+1)=SU(J,I)+DUMIF*SUI(I)
135           1+DUMS*SU(NR,I)+DUMA*SU(LARO,I)-DUMO*SU(J,I)
136           1+DUMB*SU(LBRO,I)+DUMIR*SU(K,I)
137            NU(J,I+1)=NU(J,I)+DUMIF*NUI(I)
138           1+DUMS*NU(NR,I)+DUMA*NU(LARO,I)-DUMO*NU(J,I)
139           1+DUMB*NU(LBRO,I)+DUMIR*NU(K,I)
140            XA(J,I+1)=XA(J,I)+YH*SYNTH(J,I)-BHT*XA(J,I)*DT
141           1+DUMS*XAR(I)+DUMA*XA(LARO,I)-DUMO*XA(J,I)
142           1+DUMB*XA(LBRO,I)+DUMIR*XA(K,I)
143            XE(J,I+1)=XE(J,I)+F*BHT*XA(J,I)*DT
144           1+DUMS*XER(I)+DUMA*XE(LARO,I)-DUMO*XE(J,I)
145           1+DUMB*XE(LBRO,I)+DUMIR*XE(K,I)
146            XI(J,I+1)=XI(J,I)+DUMIF*XII(I)
147           1+DUMS*XIR(I)+DUMA*XI(LARO,I)-DUMO*XI(J,I)
148           1+DUMB*XI(LBRO,I)+DUMIR*XI(K,I)
149            NON(J,I+1)=NON(J,I)+DUMIF*NONI(I)-CVNON/RDT
150           1+DUMS*NON(NR,I)+DUMA*NON(LARO,I)-DUMO*NON(J,I)
151           1+DUMB*NON(LBRO,I)+DUMIR*NON(K,I)
152           2+FOE*SCERN/RDT-FOS*FN*YH*SYNTH(J,I)
153           3-FNS*(SCIP/P-SCVO)
154            AMON(J,I)=(CVNON/RDT+(1.0-FOE)*SCERN/RDT)
155           1-(1.0-FOS)*FN*YH*SYNTH(J,I)
156            ALK(J,I+1)=ALK(J,I)+DUMIF*ALKI(I)
157           1+DUMS*ALK(NR,I)+DUMA*ALK(LARO,I)-DUMO*ALK(J,I)
158           1+DUMB*ALK(LBRO,I)+DUMIR*ALK(K,I)
159           1-7.14*NIT(J,I)+3.57*AMON(J,I)
160            XV(J,I+1)=XS(J,I+1)+XA(J,I+1)+XE(J,I+1)+XI(J,I+1)
161            RETURN
162            END
```

```
      C*****************************************************************
            SUBROUTINE ANOMOD(D,DT,J,I,FR,FBS,FCS,KVT,KMPT,KSPT,KMST,KSST,
           1P,NR,YH,BHT,F,KRT,FOE,FN,FOS,FNS,NJ,DDT,UMT,YN,KNT,RDT,BNT,
           2FACT,LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR)
      C*****************************************************************
      C              THIS SUBROUTINE CALCULATES THE DYNAMIC RESPONSE OF A
      C                REACTOR IN A SERIES UNDER ANOXIC CONDITIONS
      C*****************************************************************
            PARAMETER NE=1
            PARAMETER NEE=2
            PARAMETER ND=241
            PARAMETER NDD=242
            INTEGER D
            DOUBLE PRECISION DT,DDT,RDT
            COMMON/EXTC/SBS(NE,ND),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
           1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,ND),NH3(NE,ND),
           2NO3(NE,ND),SBP(NE,ND),ALK(NE,ND)
            COMMON/BLOCKC/Q(NEE,NDD),V(NE),SBI(ND),SUI(ND),NIT(NE,ND),
           1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),ALKI(ND),
           2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(ND),SYNTH(NE,ND),QAV(NEE),
           3ANPOT(NE,ND),AMON(NE,ND),DSFCTR(NE)
            REAL KVT,KMPT,KSPT,KMST,KSST,KRT,KNT
            REAL NUI,NONI,NH3I,NO3I,NIT
            REAL NU,NON,NH3,NO3
            REAL NH3A,NH3S,NH3T,NH3B,NH3K,NITT,NNIT,NO3A,NO3S,NO3T,NO3B,NO3K
            RNCOD=2.85/(1.0-P*YH)
      C*****************************************************************
            CALL DUMVCY(J,I,DUMIF,DUMS,DUMA,DUMB,DUMIR,DUMO,
           1LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR,
           1DT,DDT,RDT)
      C*****************************************************************
            K=J-1
            IF(K.EQ.0) K=1
            SCER=P*(1.0-F)*BHT*XA(J,I)*DDT
            SCERN=FN*SCER/P
            CVNON=KRT*XA(J,I)*NON(J,I)*DDT
            SCVOD=KMPT*XS(J,I)/(KSPT*XA(J,I)+XS(J,I)*P)*FACT*XA(J,I)*DDT
            SCVO=0.00
            SCIS=0.00
            NNIT=0.00
            ANPOTS=0.00
            SBST=SBS(J,I)
            DFSBSS=(SBS(NR,I+1)-SBS(NR,I))/NJ
            DFSBSA=(SBS(LARO,I+1)-SBS(LARO,I))/NJ
            DFSBSB=(SBS(LBRO,I+1)-SBS(LBRO,I))/NJ
            DFSBSK=(SBS(K,I+1)-SBS(K,I))/NJ
            NH3T=NH3(J,I)
            DFNH3S=(NH3(NR,I+1)-NH3(NR,I))/NJ
            DFNH3A=(NH3(LARO,I+1)-NH3(LARO,I))/NJ
            DFNH3B=(NH3(LBRO,I+1)-NH3(LBRO,I))/NJ
            DFNH3K=(NH3(K,I+1)-NH3(K,I))/NJ
            NO3T=NO3(J,I)
            DFNO3S=(NO3(NR,I+1)-NO3(NR,I))/NJ
            DFNO3A=(NO3(LARO,I+1)-NO3(LARO,I))/NJ
            DFNO3B=(NO3(LBRO,I+1)-NO3(LBRO,I))/NJ
            DFNO3K=(NO3(K,I+1)-NO3(K,I))/NJ
            XNT=XN(J,I)
            DFXNS=(XNR(I+1)-XNR(I))/NJ
            DFXNA=(XN(LARO,I+1)-XN(LARO,I))/NJ
            DFXNB=(XN(LBRO,I+1)-XN(LBRO,I))/NJ
            DFXNK=(XN(K,I+1)-XN(K,I))/NJ
            DO 12 IJ=1,NJ,1
            SCVOT=SCVOD
```

```
64              SCIST=KMST*SBST/(KSST+SBST)*FACT*XA(J,I)*DDT
65              SYNTHT=SCVOT*P+SCIST
66              DENCAP=SYNTHT/RNCOD
67              DENIT=DENCAP
68              RDEN=SCIST/SYNTHT
69              ANPOTT=0.00
70              IF((NO3T-DENIT).GT.0.00) GO TO 13
71              DENIT=NO3T
72              SYNTHT=DENIT*RNCOD
73              SCIST=SYNTHT*RDEN
74              SCVOT=SYNTHT*(1.0-RDEN)/P
75              ANPOTT=DENCAP-DENIT
76           13 CONTINUE
77              SCVO=SCVO+SCVOT
78              SCIS=SCIS+SCIST
79              ANPOTS=ANPOTS+ANPOTT
80              SBSS=SBS(NR,I)+(IJ-1)*DFSBSS
81              SBSA=SBS(LARO,I)+(IJ-1)*DFSBSA
82              SBSB=SBS(LBRO,I)+(IJ-1)*DFSBSB
83              SBSK=SBS(K,I)+(IJ-1)*DFSBSK
84              SBST=SBST+DUMIF*FBS*SBI(I)-SCIST+FCS*SCER
85             1+DUMS*SBSS+DUMA*SBSA-DUMO*SBST
86             1+DUMB*SBSB+DUMIR*SBSK
87              IF(SBST.LT.0.00) SBST=0.00
88              NITT=0.00
89              NNIT=NNIT+NITT
90              NH3S=NH3(NR,I)+(IJ-1)*DFNH3S
91              NH3A=NH3(LARO,I)+(IJ-1)*DFNH3A
92              NH3B=NH3(LBRO,I)+(IJ-1)*DFNH3B
93              NH3K=NH3(K,I)+(IJ-1)*DFNH3K
94              NO3S=NO3(NR,I)+(IJ-1)*DFNO3S
95              NO3A=NO3(LARO,I)+(IJ-1)*DFNO3A
96              NO3B=NO3(LBRO,I)+(IJ-1)*DFNO3B
97              NO3K=NO3(K,I)+(IJ-1)*DFNO3K
98              TNH3T=NH3T+DUMIF*NH3I(I)+CVNON-NITT
99             1+DUMS*NH3S+DUMA*NH3A-DUMO*NH3T
100            1+DUMB*NH3B+DUMIR*NH3K
101            1+(1.0-FOE)*SCERN-(1.0-FOS)*FN*YH*SYNTHT
102             IF(TNH3T.GT.0.0) GO TO 43
103             NH3T=0.0
104             NO3T=NO3T+DUMIF*NO3I(I)+NITT-DENIT+TNH3T
105            1+DUMS*NO3S+DUMA*NO3A-DUMO*NO3T
106            1+DUMB*NO3B+DUMIR*NO3K
107             IF(NO3T.LT.0.00) NO3T=0.00
108             GO TO 44
109          43 NH3T=TNH3T
110             NO3T=NO3T+DUMIF*NO3I(I)+NITT-DENIT
111            1+DUMS*NO3S+DUMA*NO3A-DUMO*NO3T
112            1+DUMB*NO3B+DUMIR*NO3K
113             IF(NO3T.LT.0.00) NO3T=0.00
114          44 XNS=XNR(I)+(IJ-1)*DFXNS
115             XNA=XN(LARO,I)+(IJ-1)*DFXNA
116             XNB=XN(LBRO,I)+(IJ-1)*DFXNB
117             XNK=XN(K,I)+(IJ-1)*DFXNK
118             XNT=XNT+YN*NITT-BNT*XNT*DDT
119            1+DUMS*XNS+DUMA*XNA-DUMO*XNT
120            1+DUMB*XNB+DUMIR*XNK
121          12 CONTINUE
122             SYNTH(J,I)=SCVO*P+SCIS
123             ANPOT(J,I)=ANPOTS
124             NIT(J,I)=NNIT
125             SBS(J,I+1)=SBST
126             NH3(J,I+1)=NH3T
127             NO3(J,I+1)=NO3T
```

```
128            XN(J,I+1)=XNT
129            DUMIF=DUMIF/RDT
130            DUMIR=DUMIR/RDT
131            DUMA=DUMA/RDT
132            DUMB=DUMB/RDT
133            DUMS=DUMS/RDT
134            DUMO=DUMO/RDT
135            BRAK=FR-(XS(J,I)/(FACT*XA(J,I)))
136            IF(BRAK.GT.0.00) GO TO 40
137            BRAK=0.00
138            XS(J,I)=FR*(FACT*XA(J,I))
139         40 XV(J,I)=XS(J,I)+XA(J,I)+XE(J,I)+XI(J,I)
140            SCIP=DT*KVT*BRAK*SBP(J,I)*FACT*XA(J,I)
141            SBP(J,I+1)=SBP(J,I)+DUMIF*(1.0-FBS)*SBI(I)-SCIP
142           1+DUMS*SBPR(I)+DUMA*SBP(LARO,I)-DUMO*SBP(J,I)
143           1+DUMB*SBP(LBRO,I)+DUMIR*SBP(K,I)
144           2+(1.0-FCS)*SCER/RDT
145            IF(SBP(J,I+1).LT.0.0) SBP(J,I+1)=0.0
146            XS(J,I+1)=XS(J,I)+SCIP/P-SCVO
147           1+DUMS*XSR(I)+DUMA*XS(LARO,I)-DUMO*XS(J,I)
148           1+DUMB*XS(LBRO,I)+DUMIR*XS(K,I)
149            IF(XS(J,I+1).LT.0.0) XS(J,I+1)=0.0
150            SU(J,I+1)=SU(J,I)+DUMIF*SUI(I)
151           1+DUMS*SU(NR,I)+DUMA*SU(LARO,I)-DUMO*SU(J,I)
152           1+DUMB*SU(LBRO,I)+DUMIR*SU(K,I)
153            NU(J,I+1)=NU(J,I)+DUMIF*NUI(I)
154           1+DUMS*NU(NR,I)+DUMA*NU(LARO,I)-DUMO*NU(J,I)
155           1+DUMB*NU(LBRO,I)+DUMIR*NU(K,I)
156            XA(J,I+1)=XA(J,I)+YH*SYNTH(J,I)-BHT*XA(J,I)*DT
157           1+DUMS*XAR(I)+DUMA*XA(LARO,I)-DUMO*XA(J,I)
158           1+DUMB*XA(LBRO,I)+DUMIR*XA(K,I)
159            XE(J,I+1)=XE(J,I)+F*BHT*XA(J,I)*DT
160           1+DUMS*XER(I)+DUMA*XE(LARO,I)-DUMO*XE(J,I)
161           1+DUMB*XE(LBRO,I)+DUMIR*XE(K,I)
162            XI(J,I+1)=XI(J,I)+DUMIF*XII(I)
163           1+DUMS*XIR(I)+DUMA*XI(LARO,I)-DUMO*XI(J,I)
164           1+DUMB*XI(LBRO,I)+DUMIR*XI(K,I)
165            NON(J,I+1)=NON(J,I)+DUMIF*NONI(I)-CVNON/RDT
166           1+DUMS*NON(NR,I)+DUMA*NON(LARO,I)-DUMO*NON(J,I)
167           1+DUMB*NON(LBRO,I)+DUMIR*NON(K,I)
168           2+FOE*SCERN/RDT-FOS*FN*YH*SYNTH(J,I)
169           3-FNS*(SCIP/P-SCVO)
170            AMON(J,I)=(CVNON/RDT+(1.0-FOE)*SCERN/RDT)
171           1-(1.0-FOS)*FN*YH*SYNTH(J,I)
172            ALK(J,I+1)=ALK(J,I)+DUMIF*ALKI(I)
173           1+DUMS*ALK(NR,I)+DUMA*ALK(LARO,I)-DUMO*ALK(J,I)
174           1+DUMB*ALK(LBRO,I)+DUMIR*ALK(K,I)
175           1+3.57*(SYNTH(J,I)/RNCOD+AMON(J,I))
176            XV(J,I+1)=XS(J,I+1)+XA(J,I+1)+XE(J,I+1)+XI(J,I+1)
177            RETURN
178            END
```

```
1       C*****************************************************************
2             SUBROUTINE DSTRCY(CRIT,VP,XVSS,NR,LINI,LSRI,LARI,LARO,LBRI,LBRO,
3            1QSR,QAR,QBR,SR,AR,BR,DT,DDT,RDT,NLL)
4       C*****************************************************************
5       C            THIS SUBROUTINE DISTRIBUTES THE SLUDGE MASS IN THE
6       C             PROCESS TO EACH REACTOR IN ACCORDANCE WITH THE PROCESS
7       C             CONFIGURATION INPUT DATA AND CALCULATES THE SLUDGE
8       C             CONCENTRATION IN EACH REACTOR AS A FRACTION OF THE
9       C             AVERAGE PROCESS SLUDGE CONCENTRATION
10      C*****************************************************************
11            PARAMETER NE=1
12            PARAMETER NEE=2
13            PARAMETER ND=241
14            PARAMETER NDD=242
15            DOUBLE PRECISION DT,DDT,RDT
16            COMMON/EXTC/SBS(NE,ND),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
17           1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,ND),NH3(NE,ND),
18           2NO3(NE,ND),SBP(NE,ND),ALK(NE,ND)
19            COMMON/BLOCKC/Q(NEE,NDD),V(NE),SBI(ND),SUI(ND),NIT(NE,ND),
20           1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),ALKI(ND),
21           2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(ND),SYNTH(NE,ND),QAV(NEE),
22           3ANPOT(NE,ND),AMON(NE,ND),DSFCTR(NE)
23            DIMENSION XBGN(NE),STXBGN(NE)
24            CRITXB=CRIT*XVSS*0.001
25            I=NLL
26            DO 1 J=1,NR,1
27            XBGN(J)=XVSS
28            Q(J,I)=QAV(1)
29          1 CONTINUE
30            MM=0
31          7 DO 2 J=1,NR,1
32            STXBGN(J)=XBGN(J)
33          2 CONTINUE
34            DO 3 J=1,NR,1
35            K=J-1
36            IF(K.EQ.0) K=1
37      C*****************************************************************
38            CALL DUMVCY(J,I,DUMIF,DUMS,DUMA,DUMB,DUMIR,DUMO,
39           1LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR,
40           1DT,DDT,RDT)
41      C*****************************************************************
42            XBGN(J)=XBGN(J)+DUMA*XBGN(LARO)+DUMB*XBGN(LBRO)
43           1+DUMS*(1+SR)/SR*XBGN(NR)+DUMIR*XBGN(K)-DUMO*XBGN(J)
44          3 CONTINUE
45            DO 4 J=1,NR,1
46            IF(ABS(XBGN(J)-STXBGN(J)).GE.CRITXB) GO TO 5
47          4 CONTINUE
48            GO TO 6
49          5 MM=MM+1
50            IF(MM.GE.5000) GO TO 6
51            GO TO 7
52          6 CONTINUE
53            TXBGNO=0.0
54            DO 9 J=1,NR,1
55            TXBGNO=TXBGNO+V(J)*XBGN(J)
56            DSFCTR(J)=XBGN(J)/XVSS
57          9 CONTINUE
58            XBAL=TXBGNO/(XVSS*VP)*100
59            WRITE(5,104) MM,XVSS,XBAL
60        104 FORMAT(1H0,5X,'NO. OF STEPS TO REACH STEADY STATE= ',I5,/,
61           11H ,5X,'AVERAGE PROCESS SLUDGE CONCENTRATION= ',F6.1,/,
62           11H ,5X,'PERCENTAGE SLUDGE RECOVERY = ',F7.3)
63            WRITE(5,105) (DSFCTR(J),J=1,NR,1)
```

```
64          105 FORMAT((1H ,5X,F10.4))
65              RETURN
66              END
```

```
      C*********************************************************************
            SUBROUTINE DUMVCY(J,I,DUMIF,DUMS,DUMA,DUMB,DUMIR,DUMO,
           1LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR,
           1DT,DDT,RDT)
      C*********************************************************************
      C              THIS SUBROUTINE CALCULATES THE DUMMY VALUES
      C              FROM THE PROCESS CONFIGURATION INPUT DATA
      C*********************************************************************
            PARAMETER NE=1
            PARAMETER NEE=2
            PARAMETER ND=241
            PARAMETER NDD=242
            DOUBLE PRECISION DT,DDT,RDT
            COMMON/EXTC/SBS(NE,ND),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
           1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,ND),NH3(NE,ND),
           2NO3(NE,ND),SBP(NE,ND),ALK(NE,ND)
            COMMON/BLOCKC/Q(NEE,NDD),V(NE),SBI(ND),SUI(ND),NIT(NE,ND),
           1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),ALKI(ND),
           2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(ND),SYNTH(NE,ND),QAV(NEE),
           3ANPOT(NE,ND),AMON(NE,ND),DSFCTR(NE)
            DUMIF=0.0
            IF(J.EQ.LINI) DUMIF=DDT*Q(J,I)/V(J)
            DUMS=0.0
            IF(J.EQ.LSRI) DUMS=DDT*QSR/V(J)
            DUMA=0.0
            IF(J.EQ.LARI.AND.J.LT.LARO) DUMA=DDT*QAR/V(J)
            DUMB=0.0
            IF(J.EQ.LBRI.AND.J.LT.LBRO) DUMB=DDT*QBR/V(J)
            IF(J.EQ.1) GO TO 11
            IF(J.LE.LINI.AND.J.GT.LSRI) DUMIR=DDT*QSR/V(J)
            IF(J.LE.LINI.AND.J.LE.LSRI.AND.J.GT.LBRI.AND.J.LE.LBRO)
           1DUMIR=DDT*QBR/V(J)
            IF(J.LE.LINI.AND.J.LE.LSRI.AND.J.GT.LARI.AND.J.LE.LARO)
           1DUMIR=DDT*QAR/V(J)
            IF(J.LE.LINI.AND.J.LE.LSRI.AND.J.GT.LARI.AND.J.LE.LARO.
           1AND.J.GT.LBRI.AND.J.LE.LBRO) DUMIR=DDT*(QAR+QBR)/V(J)
            IF(J.LE.LINI.AND.J.GT.LSRI.AND.J.GT.LARI.AND.J.LE.LARO)
           1DUMIR=DDT*(QSR+QAR)/V(J)
            IF(J.LE.LINI.AND.J.GT.LSRI.AND.J.GT.LBRI.AND.J.LE.LBRO)
           1DUMIR=DDT*(QSR+QBR)/V(J)
            IF(J.LE.LINI.AND.J.GT.LSRI.AND.J.GT.LARI.AND.J.LE.LARO.
           1AND.J.GT.LBRI.AND.J.LE.LBRO) DUMIR=DDT*(QSR+QAR+QBR)/V(J)
            IF(J.GT.LINI.AND.J.GT.LSRI) DUMIR=DDT*(Q(J,I)+QSR)/V(J)
            IF(J.GT.LINI.AND.J.LE.LSRI.AND.J.GT.LBRI.AND.J.LE.LBRO)
           1DUMIR=DDT*(Q(J,I)+QBR)/V(J)
            IF(J.GT.LINI.AND.J.LE.LSRI.AND.J.GT.LARI.AND.J.LE.LARO)
           1DUMIR=DDT*(Q(J,I)+QAR)/V(J)
            IF(J.GT.LINI.AND.J.GT.LSRI.AND.J.GT.LARI.AND.J.LE.LARO)
           1DUMIR=DDT*(Q(J,I)+QAR+QSR)/V(J)
            IF(J.GT.LINI.AND.J.GT.LSRI.AND.J.GT.LBRI.AND.J.LE.LBRO)
           1DUMIR=DDT*(Q(J,I)+QBR+QSR)/V(J)
            IF(J.GT.LINI.AND.J.GT.LSRI.AND.J.GT.LARI.AND.J.LE.LARO.
           1AND.J.GT.LBRI.AND.J.LE.LBRO) DUMIR=DDT*(Q(J,I)+QSR+QAR+QBR)/V(J)
           11 CONTINUE
            IF(J.EQ.1) DUMIR=0.0
            DUMO=DUMIF+DUMIR+DUMS+DUMA+DUMB
            RETURN
            END
```

PROGRAM A.2

```
1       C*********************************************************************
2       C
3       C              UNSTEADY STATE PROGRAM AS AT 5-5-1981
4       C
5       C*********************************************************************
6       C*********************************************************************
7       C
8       C           ''THIS PROGRAMME IS THE JOINT PROPERTY OF THE
9       C           UNIVERSITY OF CAPE TOWN AND THE WATER RESEARCH
10      C           COMMISSION OF SOUTH AFRICA. BEFORE USER MAY
11      C           LEGALLY UTILIZE IT, HE MUST OBTAIN THE NECESSARY
12      C           AUTHORIZATION, I.E.:
13      C
14      C           (A) IN THE CASE OF STUDENTS AT THE UNIVERSITY OF
15      C               CAPE TOWN WHO WILL USE THE PROGRAMME FOR
16      C               EDUCATIONAL PURPOSES ONLY, THIS AUTHORIZATION
17      C               CAN BE OBTAINED FROM PROF. G. VAN R. MARAIS
18      C               OF THE UNIVERSITY OF CAPE TOWN, AND
19      C           (B) IN ALL OTHER CASES, WRITTEN AUTHORIZATION
20      C               MUST BE OBTAINED FROM BOTH THE UNIVERSITY
21      C               OF CAPE TOWN (PRIVATE BAG, RONDEBOSCH, 7700,
22      C               CAPE, SOUTH AFRICA) AND THE WATER RESEARCH
23      C               COMMISSION (P.O. BOX 824, PRETORIA, 0001,
24      C               SOUTH AFRICA)''
25      C
26      C*********************************************************************
27      C*********************************************************************
28      C
29      C
30      C     THE FOLLOWING EXPLANATION REFERS TO :
31      C
32      C     ' VAN HAANDEL,C.A. AND MARAIS,G.V.R. (1981) ''KINETICS OF
33      C       NITRIFICATION AND DENITRIFICATION IN SINGLE SLUDGE ACTIVATED
34      C       SLUDGE PROCESS'', RES. REPT. NO.39, DEPT. OF CIVIL ENG.,
35      C       UNIVERSITY OF CAPE TOWN
36      C
37      C          THIS PROGRAM IS USED TO SIMULATE THE RESPONSE OF SERIES
38      C          REACTOR ACTIVATED SLUDGE SYSTEMS UNDER UNSTEADY STATE
39      C          CONDITIONS.THE REACTORS ARE ASSUMED TO BE COMPLETELY
40      C          MIXED . THE VALUES OF THE VARIABLES ARE CALCULATED AS
41      C          A FUNCTION OF TIME USING THE SUPPLIED STARTING VALUES
42      C          AND THE KINETIC EXPRESSIONS DEVELOPED BY DOLD, EKAMA
43      C          AND MARAIS FOR AN AEROBIC ENVIRONMENT (I.E. THE BI-
44      C          SUBSTRATE /DEATH REGENERATION/ACTIVE SITE THEORY) OR
45      C          THOSE LISTED IN TABLE (4.1 CHAPTER 4) FOR AN ANOXIC
46      C          ENVIRONMENT. THE CALCULATED VALUES OF ALL THE VARIABLES
47      C          IN EACH REACTOR CAN BE PRINTED AS A FUNCTION OF TIME
48      C          AND/OR WRITTEN TO A PLOT FILE FOR SUBSEQUENT PLOTTING
49      C          TOGETHER WITH EXPERIMENTAL DATA.THE PLOTTING PROGRAM IS
50      C          LISTED IN APPENDIC A.6
51      C          THE RESPONSE IS CALCULATED OVER THE PERIOD THAT INPUT
52      C          FLOW AND LOAD DATA IS SUPPLIED
53      C          THE REQUIRED PERIOD OF PLOTTED RESPONSE MUST BE SPECIFIED
54      C          THE MAIN PROGRAM HAS FOUR SUBROUTINES:
55      C        1)UDUMV CALCULATES THE HYDRAULIC EFFCTS IN THE REACTORS
56      C        2)UAERO CALCULATES THE RESPONSE OF A REACTOR IN AN AEROBIC
57      C          ENVIRONMENT
58      C        3)UANOX CALCULATES THE RESPONSE OF A REACTOR IN AN ANOXIC
59      C          ENVIRONMENT
60      C        4)USETL CALCUALTES THE RESPONSE OF THE SETTLER
61      C
62      C             THE PROGRAM AS LISTED BELOW IS SUBJECTED TO THE FOLLOWING
63      C             LIMITATIONS
```

```
      C            1)THE LENGTHS OF THE ANOXIC AND THE AEROBIC PERIODS IN
      C              A REACTOR ARE FOR ONE CYCLE CAN EACH ASSUME ONE VALUE ONLY
      C            2)THE INFLUENT FOLW CAN ONLY BE INTRODUCED INTO ONE
      C              REACTOR
      C            3) THE RECYCLE FLOW FROM THE SETTLER CAN ONLY BE CONVEYED
      C               TO ONE REACTOR (WHICH IS NOT NECESSARILY THE FIRST ONE)
      C            4) IT IS ONLY POSSIBLE TO HAVE TWO INTERNAL RECYCLES FLOWS
      C              (A AND B) EACH OF WHICH CONVEYS MIXED LIQUOR FROM ONE
      C              REACTOR TO ANOTHER THE LATTER BEING NEARER TO THE REACTOR
      C               RECIEVING THE INFLUENT
      C            5) ALL RECYCLE FLOWS ARE CONSTANT WITH TIME.
      C            6) OPTIONS FOR THE INFLUENT FLOW PATTERN ARE:
      C               A)SINOIDAL
      C               B)SQUARE WAVE
      C               C)GENERAL PATTERN WITH LINEAR INTERPOLATION
      C            7)THE CONCENTRATION PATTERNS OF INFLUENT COD,TKN,NITRATE
      C              AND ALKALINITY HAVE THE SAME LIMITATIONS AS MENTIONED
      C              FOR THE INFLUENT FLOW UNDER 6
      C            8)IT IS ASSUMED THAT DURING A CYCLE THE CONSTANTS CHARA
      C              CHARACTERIZING THE SEWAGE (FUS,FUP,FBS,FUN,FAN,SN) DO
      C              NOT CHANGE
      C            9)IT IS ASSUMED THAT THE D.O. CONCENTRATION IN THE AEROBIC
      C              REACTORS IS SUFFICIENT SO THAT IT DOES NOT LIMIT THE
      C              RATES OF UTILIZATION OF ORGANIC SUBSTRATE OR OF NITRI-
      C              FICATION
      C           10)IT IS ASSUMED THAT ANY D.O. RECYCLED TO YHE ANOXIC
      C              REACTORS DOES NOT AFFECT THE RATE OF DENITRIFICATION
      C           11)THE PH AND TEMPERATURE ARE ASSUMED TO BE CONSTANT
      C              OVER ONE CYCLE AND THE SAME IN ALL REACTORS
      C           12)IS IS ASSUMED THAT THE PROCESS IS A SINGLE SLUDGE
      C              PROCESS I.E. THERE IS ONLY ONE SETTLER
      C           13) IT IS ASSUMED THAT SLUDGE WASTAGE TAKES PLACE FROM
      C               ONE OR MORE REACTORS.THE FLOW OF WASTED SLUDGE IS CON-
      C              STANT DURING THE PERIOD OF WASTAGE AND PROPORTIONAL
      C              TO THE REACTOR VOLUME.
      C            14) THE SETTLER IS TAKEN AS AN IDEAL LIQUID SOLID
      C                SEPARATOR, I.E. THE RETENTION TIME IN THE SETTLER
      C                IS ZERO AND NO REACTION TAKES PLACE IN THE SETTLER.
      C
      C               ALL THE LIMITATIONS ABOVE ,EXCEPT THE LAST ONE, ARE
      C              IMPOSED TO REDUCE THE REQIRED CORE STORAGE. IF
      C              REQUIRED THR PROGRAM CAN BE REWRITTEN IN SUCH
      C              FASHION THAT NONE OF THE LIMITATIONS 1 TO 13 APPLY.
      C              THE FOURTEENTH LIMITATION CAN BE OMITTED ONLY IF SUFF
      C              SUFFICIENT DATA IS AVAILABLE TO DESCRIBE THE
      C              SETTLING BEHAVOUR UNDER CYCLIC FLOW AND LOAD
      C              CONDITIONS.
      C
      C           NOTE THAT THIS PROGRAM CAN ONLY BE USED TO CHECK A
      C           DESIGN AND HENCE REQUIRES A DESIGN CONFIGURATION
      C           WITH SPECIFIED REACTOR VOLUMES.
      C
      C           THE PROGRAM HAS BEEN TESTED FOR DIFFERENT VARIANTS
      C           OF THE ACTIVATED SLUDGE PROCESS, I.E.
      C           1)SERIES SUSPENSION MIXED AERATED LAGOONS
      C           2)CONTACT STABILIZATION PROCESS
      C           3)OXIDATION DITCH
      C           4)SERIES COMPLETELY NIXED REACTOR SYSTEM(1 TO 6 REACTORS)
      C           WITH AND WITHOUT ANOXIC REACTORS.
      C
      C*************************************************************************
      C*************************************************************************
      C
      C         INPUT OF DATA
```

```
C          -------------
C
C          FIRST CARD:
C          ----------
C
C          TYPE = LOGICAL NUMBER DESCRIBING INFLUENT LOAD PATTERN
C            IF = 1   SINE WAVE LOAD PATTERN
C            IF = 2   SQUARE WAVE LOAD PATTERN
C            IF = 3   GENERAL LOADING PATTERN
C        RESULT = LOGICAL NUMBER TO DIRECT OUTPUT
C            IF = 1    PRINT RESULTS
C            IF = 2    PLOT RESULTS
C            IF = 0    PLOT AND PRINT RESULTS
C           KOM = TIME AT WHICH TIME BASE COUNTER COMMENCES
C           NDH = LENGTH OF PERIOD OF PLOTTED SIMULATION
C             M = LENGTH OF PERIOD OF CALCULATED SIMULATION
C             DATE,XMONTH AND YEAR REFER TO THE DATE THE EXPERIMENT
C             TO BE SIMULATED WAS CARRIED OUT.
C
C
C             SECOND CARD
C             -----------
C             (INPUT FLOW AND LOAD)
C            Q0 = AVERAGE INFLUENT FLOW FOR SINE WAVE PATTERN
C          STI0 = INFLUENT COD CONCENTRATION DURING PEAK FLOW PERIOD FOR
C                 SQUARE WAVE PATTERN OR AVERAGE FOR SINE WAVE PATTERN
C          NTI0 = INFLUENT TKN CONCENTRATION DURING PEAK FLOW PERIOD FOR
C                 SQUARE WAVE PATTERN OR AVERAGE FOR SINE WAVE PATTERN
C         NO3I0 = INFLUENT NO3 CONCENTRATION DURING PEAK FLOW PERIOD FOR
C                 SQUARE WAVE PATTERN OR AVERAGE FOR SINE WAVE PATTERN
C         ALKI0 = INFLUENT ALK CONCENTRATION DURING PEAK FLOW PERIOD FOR
C                 SQUARE WAVE PATTERN OR AVERAGE FOR SINE WAVE PATTERN
C        VARSTI = AMPLITUDE OF INPUT COD CONC. WAVE (SINE WAVE)
C        VARNTI = AMPLITUDE OF INPUT TKN CONC. WAVE (SINE WAVE)
C         VNO3I = AMPLITUDE OF INPUT NO3 CONC. WAVE (SINE WAVE)
C          VARQ = AMPLITUDE OF INFLUENT FLOW WAVE (SINE WAVE)
C         STI00 = INFLUENT COD CONCENTRATION DURING BASE FLOW PERIOD
C         NTI00 = INFLUENT TKN CONCENTRATION DURING BASE FLOW PERIOD
C        NO3I00 = INFLUENT NO3 CONCENTRATION DURING BASE FLOW PERIOD
C        ALKI00 = INFLUENT ALK CONCENTRATION DURING BASE FLOW PERIOD
C           LFP = LENGTH OF FEED PERIOD (SQUARE WAVE)
C            PQ = PEAK FLOW RATE IN SQUARE WAVE PATTERN
C            BQ = BASE FLOW RATE IN SQUARE WAVE PATTERN
C            VF = VOLUME OF FEED PER DAY
C         START = BEGIN FEEDING PERIOD (SQ.WAVE)
C
C          THIRD CARD
C          ----------
C          (KINETIC CONSTANTS AND MASS PARAMETERS)
C
C           AN EXTRA T OR 20 INDICATES VALUES AT T OR 20 DEG. C
C            KV = MAX. RATE OF COD TRANSFER FROM SEWAGE INTO STORAGE
C            KR = RATE OF CONVERSION OF ORGANIC N TO SALINE NH3
C           KMP = MAX. RATE OF  ORGANISM SYNTHESIS FROM STORED COD
C           KMS = MAX. RATE OF  ORGANISM SYNTHESIS FROM SOLUBLE COD
C           KSP = HALF SATURATION COEF. FOR STORED COD  UTILIZATION
C           KSS = HALF SATURATION COEF. FOR SOLUBLE COD  UTILIZATION
C            UM = MAXIMUM GROWTH RATE OF NITRIFYING ORGANISMS
C            KN = HALF SATURATION COEF. FOR NH3  UTILIZATION
C            BH = DEATH RATE
C            BN = DEATH RATE FOR NITRIFICATION
C            YH = YIELD OF ORGANISMS FROM COD UTILIZED
C            YN = ACTIVE MASS YIELD OF NITRIFYING ORGANISMS FROM AMMONIA
C             F = UNBIODEG. FRACTION OF ORGANISM
```

```
C           SR = UNDERFLOW RECYCLE  RATIO
C           AR = A-RECYCLE RATIO
C           BR = B-RECYCLE RATIO
C
C           EIGHTH CARD
C           -----------
C           (ANOXIC SLUDGE MASS FRACTION)
C           INIT = INITIAL AEROBIC PERIOD
C           ANOX = DURATION OF AN ANOXIC PERIOD]
C           AROB = DUARTION OF AN AEROBIC PERIOD
C         NOTE
C         ----
C           NITROGEN CONCENTRATIONS MEASURED IN MG-N/L WITH TKN TEST
C           COD CONCENTRATIONS MEASURED IN MG/L OF COD
C           VSS CONCENTRATIONS MEASURED IN MG/L OF VSS
C           OXYGEN CONSUMPTIONS IN MG/L/HOUR
C           UNIT OF MASS IS THE MG
C           UNIT OF VOLUME IS THE L
C           UNIT OF TIME IS THE DAY
C           SYMBOL S REFERS TO COD
C           SYMBOL X REFERS TO VSS
C           SYMBOL N REFERS TO NITROGEN
C           SYMBOL O REFERS TO OXYGEN
C
C
C
C       DIMENSION STATEMENTS
C       --------------------
C
            PARAMETER NE=6
            PARAMETER NEE=7
            PARAMETER ND=241
            PARAMETER NDD=242
            COMMON/EXTC/SBS(NE,ND),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
           1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,ND),NH3(NE,ND),
           2NO3(NE,ND),SBP(NE,ND),ALK(NE,ND)
            COMMON/BLOCKC/Q(NEE,NDD),V(NE),SBI(ND),SUI(ND),NIT(NE,ND),
           1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),ALKI(ND),
           2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(ND),SYNTH(NE,ND),QAV(NEE),
           3ANPOT(NE,ND),AMON(NE,ND)
            CHARACTER IMFT*19/'((20X,I4, (E13.5)))'/,CH*1
            REAL KVT,KMPT,KSPT,KMST,KSST,KRT,KNT,NTITI,NTITO
            REAL NUI,NONI,NH3I,NO3I,NIT
            REAL NU,NON,NH3,NO3
            INTEGER D,DD,HK,TYPE,RESULT,TN
            DOUBLE PRECISION DT,DDT,RDT
            DIMENSION STI(ND),STQ(ND)
            REAL NTI(ND),NTQ(ND),NO3Q(ND),NXII(ND)
            REAL NTIAV,NUIAV,NONIAV,NO3IAV,NH3IAV,NXIIAV
            REAL NTQAV,NO3QAV
            REAL NTIMAX,NO3IAX,NTQMAX,NO3QAX
            REAL NTI0,NTI00,NO3I0,NO3I00,LFP
            DIMENSION RA(NE),RN(NE),LRSD(NE),NTDN(NE,ND),INTDN(NE),ALKQ(ND)
            REAL KV20,KMP20,KSP20,KMS20,KSS20,KNMAX,KN20,KR20
            DIMENSION KO(ND),WQ(NE,ND),INIT(NE),ANOX(NE),AROB(NE),FANOX(NE),
           1OC(NE,ND),ON(NE,ND),OT(NE,ND),ST(NE,ND),RXS(NE,ND)
            REAL NT(NE,ND)
            DIMENSION SBSAV(NE),ODAV(NE),OCAV(NE),RNO3(NE),ALKAV(NE),AMAV(NE),
           1ONAV(NE),OTAV(NE),STAV(NE),SUAV(NE),SBPAV(NE),
           2XAAV(NE),XEAV(NE),XSAV(NE),XIAV(NE),XVAV(NE),
           3XNAV(NE),RXSAV(NE),NAME(NE),LNAME(3),APTAV(NE),APTNR(NE)
            REAL NONAV(NE),NTAV(NE),NO3AV(NE),NH3AV(NE),NUAV(NE),NSWAV(NE)
            REAL NONSS,NUSS,NO3SS,NH3SS
C
```

```
320      C
321      C           INPUT OF DATA
322      C           -------------
323        100 FORMAT ( )
324        101 FORMAT(2I1,I4,I3,I4,A2,A3,A4)
325            READ 101,TYPE,RESULT,KOM,NDH,M,DATE,XMONTH,YEAR
326            IF(TYPE.EQ.1) GO TO 111
327            IF(TYPE.EQ.2) GO TO 112
328            IF(TYPE.EQ.3) GO TO 113
329        111 READ 100,PI
330            WRITE (5,100)PI
331            READ 100,Q0,STI0,NTI0,NO3I0,ALKI0,VARQ,VARSTI,VARNTI,VNO3I,VALKI
332            GO TO 113
333        112 READ 100,VF,STI0,NTI0,NO3I0,ALKI0,BQ,STI00,NTI00,NO3I00,ALKI00,LFP
334           &,START
335        113 READ(8,100) KV20,KMP20,KSP20,KMS20,KSS20,UMAX,KNMAX,BH20,BN20,
336           1KR20,FOS,FBS,FR,YH,YN,F,P,FN,FOE,FACT,FCS
337            READ 100,RS,NR,D,NJ,FUS,FUP,UN,SN
338            READ 100,THEA,THEM,THES,THEE,PHIN,THEN,THEZ,TEMP,PH
339            READ(8,100) (V(J),LRSD(J),J=1,NR,1)
340            READ(8,100) ICSD,ISSD,NRSD,LINI,LSRI,LARI,LARO,LBRI,LBRO,SR,AR,BR
341            READ(8,100)(INIT(J),ANOX(J),AROB(J),J=1,NR)
342            KH=D/24
343            NL=D+1
344            NLL=D+2
345            DD=NJ*D
346            NRR=NR+1
347      C
348      C
349      C           CALCULATION CHARACTERISTICS
350      C           ---------------------------
351      C           THIS PROGRAMME REQUIRES THE FOLLOWING CORE STORAGE CAPACITY:-
352      C            FOR ND=241 AND NF=4*(ND-1)+1 AND NEE=NE+1
353      C            STORAGE=10*NE+23 KILOWORDS
354      C            KO = TIME BASE VARIABLE
355      C             D = NUMBER OF INTERGRATION STEPS PER DAY
356      C            DT = INTERGRATION STEP LENGTH
357      C            DD = NUMBER OF INTERGRATION STEPS PER DAY FOR NITRIFICATION
358      C           DDT = INTERGRATION STEP LENGTH FOR NITRIFICATION
359      C           RDT = RATIO OF INTERGRATION STEP LENGTHS
360      C            KH = NUMBER OF TIME STEPS PER HOUR
361      C            HK = NO. OF INTERVALS PER DAY  OF SLUDGE WASTAGE
362      C
363      C           SEWAGE CHARACTERISTICS
364      C           ----------------------
365      C             Q = INFLUENT FLOW
366      C           STI = TOTAL INFLUENT COD
367      C           NTI = TOTAL INFLUENT TKN
368      C           STQ = TOTAL INFLUENT COD LOAD
369      C           NTQ = TOTAL INFLUENT TKN LOAD
370      C          NO3Q = TOTAL INFLUENT NO3 LOAD
371      C          NONI = INFLUENT ORGANIC NITROGEN CONCENTRATION
372      C          NH3I = INFLUENT AMMONIA CONCENTRATION
373      C          NO3I = INFLUENT NITRATE CONCENTRATION
374      C           NUI = UNBIODEGRADABLE FRACTION OF SEWAGE N
375      C          NXII = UNSABLE N IN INERT MATERIAL IN INFLUENT
376      C           XII = UNBIODEG. SOLID FRACTION OF SEWAGE COD AS VSS
377      C           SBI = BIODEG. FRACTION OF SEWAGE COD
378      C           SUI = UNBIODEG. SOLUBLE FRACTION OF SEWAGE COD
379      C         NM,NN = LIMITS OF PEAK FLOW PERIOD
380      C          QMAX = MAXIMUM FLOW VALUE OF THE DAY
381      C        STIMAX = MAXIMUM COD CONCENTRATION VALUE OF THE DAY
382      C        NTIMAX = MAXIMUM TKN CONCENTRATION VALUE OF THE DAY
383      C        NO3IAX = MAXIMUM NO3 CONCENTRATION VALUE OF THE DAY
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C       STQMAX = MAXIMUM COD LOAD VALUE OF THE DAY
C       NTQMAX = MAXIMUM TKN LOAD VALUE OF THE DAY
C       NO3QAX = MAXIMUM NO3 LOAD VALUE OF THE DAY
C       VARSTL = AMPLITUDE OF INFLUENT COD LOAD WAVE (SINE WAVE)
C       VARNTL = AMPLITUDE OF INFLUENT TKN LOAD WAVE (SINE WAVE)
C       VRNO3L = AMPLITUDE OF INFLUENT NO3 LOAD WAVE (SINE WAVE)
C
C          PROCESS CHARACTERISTICS
C          -----------------------
C
C       NTDN = LOGICAL NUMBER DESCRIBING PROCESS OPERATION
C           IF = 1  PROCESS INCLUDES NITRIFICATION ONLY
C           IF = 1 REACTOR IS IN AN AEROBIC ENVIRONMENT
C           IF = 0 REACTOR IS IN AN ANOXIC ENVIRONMENT
C         TEMP = OPERATING TEMPERATURE OF MIXED LIQUOR
C           PH = OPERATING PH OF MIXED LIQUOR
C          RSM = MINIMUM SLUDGE AGE FOR NITRIFICATION
C           RN = NOMINAL HYDRAULIC RETENTION TIME IN REACTORS
C           RA = ACTUAL HYDRAULIC RETENTION TIME IN REACTORS
C          TRN = TOTAL HYDRAULIC RETENTION TIME OF PROCESS
C          QSR = SLUDGE UNDERFLOW RECYCLE RATE
C          QAR = MIXED LIQUOR RECYCLE RATE (A-RECYCLE)
C          QBR = MIXED LIQUOR RECYCLE RATE (B-RECYCLE)
C           NR = NUMBER OF REACTORS IN SERIES
C          NRR = NUMBER OF REACTORS IN SERIES INCLUDING CLARIFIER
C           VP = TOTAL VOLUME OF PROCESS
C         END = END FEEDING PERIOD (SQ.WAVE)
C           WQ = SLUDGE WASTE FLOW
C     N.B.  THE SLUDGE WASTE FLOW MAY NEVER BE GREATER THAN
C            THE INFLUENT FLOW AT ANY INERVAL OF THE DAY
C       I.E. THE EFFLUENT FLOW FROM A REACTOR MAY NEVER BE LESS
C            THAN ZERO AT ANY INTERVAL OF THE DAY
C
C          GENERAL NOTATION FOR PROCESS VARIABLES IN REACTOR
C          -------------------------------------------------
C
C          SBP = BIODEGRADABLE PARTICULATE COD
C          SBS = BIODEGRADABLE SOLUBLE COD
C           SU = UNBIODEGRADABLE COD
C           ST = TOTAL COD
C           XS = STORED COD
C           XA = ACTIVE ORGANISMS
C           XE = INERT RESIDUE FROM DECAYING ORGANISMS
C           XI = INERT MATERIAL FROM SEWAGE
C           XN = ACTIVE NITROSOMONAS
C           XV = TOTAL VSS
C           OA = OXYGEN CONSUMPTION RATE FOR ADSORPTION OF COD
C           OS = OXYGEN CONSUMPTION RATE FOR SYNTHESIS
C           OE = OXYGEN CONSUMPTION RATE FOR ENDOGENOUS RESPIRATION
C           OC = TOTAL CARBONACEOUS OXYGEN CONSUMPTION RATE
C           ON = OXYGEN CONSUMPTION FOR NITRIFICATION
C           OT = TOTAL OXYGEN CONSUMPTION RATE
C         AMON = AMMONIFICATION RATE (MG N/L/D)
C          NSW = NITROGEN REMOVED IN SLUDGE WASTAGE PER DAY
C           NT = TOTAL TKN IN REACTOR
C           NU = UNBIODEGRADABLE TKN IN REACTOR
C          NON = ORGANIC NITROGEN CONCENTRATION  IN REACTOR
C          NH3 = AMMONIA CONCENTRATION IN REACTOR
C          NO3 = NITRATES CONCENTRATION IN REACTOR
C          ALK = ALKALINITY CONCENTRATION IN REACTOR
C          SCI = ENERGY ENTERING STORAGE FROM LIQUID PHASE (MG-COD/L)
C         SCVO = ENERGY REMOVED FROM STORAGE DUE TO CELL SYNTHESIS (MG-V
C
C          THE SUFFIX 'AV' AFTER A SYMBOL INDICATES DAILY AVERAGE
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448      C           VALUES FOR VARIABLES IN INFLUENT OR REACTORS
449      C          THE SUFFIX 'R' AFTER A SYMBOL INDICATES
450      C           VALUES FOR VARIABLES IN RECYCLE
451      C          THE SUFFIX 'P' AFTER A SYMBOL INDICATES VALUES
452      C           FOR VARIABLES CARRIED OVER TO PLOTTER ROUTINES
453      C          THE SUFFIX 'MAV' AFTER A SYMBOL INDICATES DAILY AVERAGE
454      C           VALUES OF VARIABLES FOR PROCESS
455      C
456      C         BALC = PERCENTAGE COD RECOVERY
457      C        TCODI = TOTAL COD MASS INPUT
458      C        TCODO = TOTAL COD MASS OUTPUT
459      C        TNTI = TOTAL TKN MASS INPUT
460      C        TNTO = TOTAL TKN MASS OUTPUT
461      C        TALKI = TOTAL ALKALINITY MASS INPUT
462      C        TALKO = TOTAL ALKALINITY MASS OUTPUT
463      C        TWCOD = TOTAL COD MASS IN WASTE FLOWS FROM REACTORS
464      C        TWN  = TOTAL TKN MASS IN WASTE FLOWS FROM REACTORS
465      C        TWALK = TOTAL ALK MASS IN WASTE FLOWS FROM REACTORS
466      C         WCOD = COD MASS IN WASTE FLOW FROM REACTOR
467      C         ECOD = TOTAL COD MASS IN EFFLUENT
468      C         BALN = PERCENTAGE NITROGEN RECOVERY
469      C         TNTI = TOTAL NITROGEN MASS INPUT
470      C         TNTO = TOTAL NITROGEN MASS OUTPUT
471      C          TWN = TOTAL NITROGEN MASS IN WASTE FLOWS FROM REACTORS
472      C           WN = NITROGEN MASS IN WASTE FLOW FROM REACTOR
473      C         ECOD = TOTAL COD IN EFFLUENT
474      C           EN = TOTAL NITROGEN MASS IN EFFLUENT
475      C         EALK = TOTAL ALKALINTY IN EFFLUENT
476      C
477            IF(TYPE.EQ.1) GO TO 115
478            IF(TYPE.EQ.2) GO TO 116
479            READ(8,100) (Q(1,I),I=1,NL,KH)
480            READ(8,100) (STI(I),I=1,NL,KH)
481            READ(8,100) (NTI(I),I=1,NL,KH)
482            READ(8,100) (NO3I(I),I=1,NL,KH)
483            READ(8,100) (ALKI(I),I=1,NL,KH)
484            IF(TYPE.EQ.3) GO TO 117
485          115 DO 8 I=1,NL,KH
486            KL=(I-1)/KH
487            DUM=SIN(2*PI*(KL-8)/24)
488            Q(1,I)=Q0*(1+VARQ*DUM)
489            STI(I)=STI0*(1+VARSTI*DUM)
490            NTI(I)=NTI0*(1+VARNTI*DUM)
491            NO3I(I)=NO3I0*(1+VNO3I*DUM)
492            ALKI(I)=ALKI0*(1+VALKI*DUM)
493          8 CONTINUE
494      C
495      C        INTERPOLATION OF STI, NO3I, Q AND NTI AT REQUIRED INTERVALS
496      C        ------------------------------------------------------------
497      C
498          117 DO 25 I=1,24
499            KI=KH*I+1
500            KJ=KH*(I-1)+1
501            DIFSTI=(STI(KI)-STI(KJ))/KH
502            DIFFQ=(Q(1,KI)-Q(1,KJ))/KH
503            DIFNTI=(NTI(KI)-NTI(KJ))/KH
504            DNO3I=(NO3I(KI)-NO3I(KJ))/KH
505            DALKI=(ALKI(KI)-ALKI(KJ))/KH
506            DO 25 J=2,KH,1
507            KK=KJ+J-1
508            STI(KK)=STI(KJ)+(J-1)*DIFSTI
509            Q(1,KK)=Q(1,KJ)+(J-1)*DIFFQ
510            NTI(KK)=NTI(KJ)+(J-1)*DIFNTI
511            NO3I(KK)=NO3I(KJ)+(J-1)*DNO3I
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512            ALKI(KK)=ALKI(KJ)+(J-1)*DALKI
513           25 CONTINUE
514              GO TO 118
515          116 PQ=BQ+(VF-BQ)*24.0/LFP
516              DO 24 I=1,NL,1
517              NTI(I)=NTI00
518              STI(I)=STI00
519              Q(1,I)=BQ
520              ALKI(I)=ALKI00
521           24 NO3I(I)=NO3I00
522              NM=START*KH+1
523              END=START+LFP
524              NN=LFP*KH+NM
525              DO 23 I=NM,NN,1
526              STI(I)=STI0
527              Q(1,I)=PQ
528              NTI(I)=NTI0
529              NO3I(I)=NO3I0
530              ALKI(I)=ALKI0
531           23 CONTINUE
532          118 DO 1 I=1,NL
533              STQ(I)=STI(I)*Q(1,I)
534              NTQ(I)=NTI(I)*Q(1,I)
535              NO3Q(I)=NO3I(I)*Q(1,I)
536              ALKQ(I)=ALKI(I)*Q(1,I)
537              SUI(I)=FUS*STI(I)
538              NUI(I)=UN*NTI(I)
539              XII(I)=FUP*STI(I)
540              NXII(I)=XII(I)*FN
541              NH3I(I)=SN*NTI(I)
542              NONI(I)=NTI(I)-NUI(I)-NXII(I)-NH3I(I)
543            1 SBI(I)=STI(I)*(1.0-FUS-FUP*P)
544          C
545          C     READ IN STARTING VALUES OF THE VARIABLES
546          C
547          C
548              READ(8,100)(SBP(J,1),J=1,NR,1)
549              READ(8,100)(SBS(J,1),J=1,NR,1)
550              READ(8,100)(SU(J,1),J=1,NR,1)
551              READ(8,100)(XS(J,1),J=1,NR,1)
552              READ(8,100)(XA(J,1),J=1,NR,1)
553              READ(8,100)(XE(J,1),J=1,NR,1)
554              READ(8,100)(XI(J,1),J=1,NR,1)
555              READ(8,100)(XN(J,1),J=1,NR,1)
556              READ(8,100)(NU(J,1),J=1,NR,1)
557              READ(8,100)(NON(J,1),J=1,NR,1)
558              READ(8,100)(NH3(J,1),J=1,NR,1)
559              READ(8,100)(NO3(J,1),J=1,NR,1)
560              READ(8,100)(ALK(J,1),J=1,NR,1)
561              DO 46 J=1,NR,1
562              XV(J,1)=XS(J,1)+XA(J,1)+XE(J,1)+XI(J,1)
563          46  CONTINUE
564          C
565          C      CALCULATION OF AVERAGE SEWAGE CHARACTERISTICS
566          C      ---------------------------------------------
567          C
568              SUMQ=0
569              SUMSTI=0
570              SUMNTI=0
571              SNO3I=0.0
572              SALKI=0.0
573              QMAX=0.0
574              STIMAX=0.0
575              SUMSTQ=0.0
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576             STQMAX=0.0
577             SUMNTQ=0.0
578             NTQMAX=0.0
579             NTIMAX=0.0
580             SNO3Q=0.0
581             NO3QAX=0.0
582             NO3IAX=0.0
583             SALKQ=0.0
584             ALKQAX=0.0
585             ALKIAX=0.0
586             DO 2 I=1,D,1
587             SUMNTI=SUMNTI+NTI(I)
588             SNO3I=SNO3I+NO3I(I)
589             SALKI=SALKI+ALKI(I)
590             SUMSTI=SUMSTI+STI(I)
591             SUMSTQ=SUMSTQ+STQ(I)
592             SUMNTQ=SUMNTQ+NTQ(I)
593             SNO3Q=SNO3Q+NO3Q(I)
594             SALKQ=SALKQ+ALKQ(I)
595             IF(STQ(I).GT.STQMAX) STQMAX=STQ(I)
596             IF(NTQ(I).GT.NTQMAX) NTQMAX=NTQ(I)
597             IF(NO3Q(I).GT.NO3QAX) NO3QAX=NO3Q(I)
598             IF(ALKQ(I).GT.ALKQAX) ALKQAX=ALKQ(I)
599             IF(Q(1,I).GT.QMAX) QMAX=Q(1,I)
600             IF(STI(I).GT.STIMAX) STIMAX=STI(I)
601             IF(NTI(I).GT.NTIMAX) NTIMAX=NTI(I)
602             IF(NO3I(I).GT.NO3IAX) NO3IAX=NO3I(I)
603             IF(ALKI(I).GT.ALKIAX) ALKIAX=ALKI(I)
604           2 SUMQ=SUMQ+Q(1,I)
605             QAV(1)=SUMQ/D
606             STQAV=SUMSTQ/D
607             NTQAV=SUMNTQ/D
608             NO3QAV=SNO3Q/D
609             ALKQAV=SALKQ/D
610             IF(TYPE.EQ.2) GO TO 119
611             NTIAV=SUMNTI/D
612             STIAV=SUMSTI/D
613             NO3IAV=SNO3I/D
614             ALKIAV=SALKI/D
615             GO TO 120
616         119 STIAV=STQAV/VF
617             NTIAV=NTQAV/VF
618             NO3IAV=NO3QAV/VF
619             ALKIAV=ALKQAV/VF
620         120 SBIAV=STIAV*(1.0-FUS-FUP*P)
621             SUIAV=FUS*STIAV
622             NUIAV=NTIAV*UN
623             XIIAV=FUP*STIAV
624             NXIIAV=FN*XIIAV
625             NH3IAV=SN*NTIAV
626             NONIAV=NTIAV-NXIIAV-NUIAV-NH3IAV
627             QSR=SR*QAV(1)
628             QAR=AR*QAV(1)
629             QBR=BR*QAV(1)
630             IF(TYPE.EQ.2) GO TO 121
631             VARSTL=STQMAX/STQAV-1.00
632             VARNTL=NTQMAX/NTQAV-1.00
633             VRNO3L=NO3QAX/NO3QAV-1.00
634             IF(VRALKL.LT.0.0) VRALKL=0.0
635             IF(VRNO3L.LT.0.0) VRNO3L=0.0
636             IF(VRALKL.LT.0.0) VRALKL=0.0
637             IF(TYPE.EQ.1) GO TO 121
638             VARQ=QMAX/QAV(1)-1.00
639             VARSTI=STIMAX/STIAV-1.00
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640           VARNTI=NTIMAX/NTIAV-1.00
641           VNO3I=NO3IAX/NO3IAV-1.00
642           VALKI=ALKIAX/ALKIAV-1.00
643           IF(VNO3I.LT.0.0) VNO3I=0.0
644           IF(VALKI.LT.0.0) VALKI=0.0
645         121 CONTINUE
646       C
647       C              CALCULATE TOTAL AND AEROBIC VOLUMES
648       C              -----------------------------------
649       C
650           DO 37 J=1,NR,1
651           IFREQ=24/(ANOX(J)+AROB(J))
652           DO 37 I=1,NL,1
653           NTDN(J,I)=1
654       37  CONTINUE
655           VP=0.0
656           DO 133 J=1,NR,1
657           VP=VP+V(J)
658           DO 133 I=1,NL,1
659           DO 133 II=1,IFREQ,1
660           IB=(INIT(J)+(II-1)*(ANOX(J)+AROB(J)))*KH+1
661           IE=(INIT(J)+(II-1)*(ANOX(J)+AROB(J))+ANOX(J))*KH+1
662           IF(I.GE.IB.AND.I.LT.IE) NTDN(J,I)=0
663           NTDN(J,NL)=NTDN(J,1)
664         133 CONTINUE
665           JJ=3
666           DO 77 J=1,NR,1
667           INTDN(J)=0
668           DO 77 I=1,NL,1
669           INTDN(J)=INTDN(J)+NTDN(J,I)
670       77  CONTINUE
671           SANOX=0.0
672           DO 78 J=1,NR,1
673           IF(INTDN(J).EQ.0) JJ=1
674           IF(INTDN(J).EQ.NL) JJ=2
675           NAME(J)=LNAME(JJ)
676           FANOX(J)=1.0-INTDN(J)/NL
677           SANOX=SANOX+FANOX(J)
678       78  CONTINUE
679           LNAME(1)='AROB'
680           LNAME(2)='ANOX'
681           LNAME(3)='ANAE'
682       C
683       C              ADJUST TEMPERATURE AND PH DEPENDENT CONSTANTS
684       C              ---------------------------------------------
685       C
686           IF(PH.LT.8.0) UM20=UMAX
687           IF(PH.LT.7.2) UM20=UMAX*(PHIN)**(PH-7.20)
688           IF(PH.LT.8.0) KN20=KNMAX
689           IF(PH.LT.7.2) KN20=KNMAX*(PHIN)**(7.20-PH)
690           UMT=UM20*(THEN)**(TEMP-20.0)
691           KNT=KN20*(THEN)**(TEMP-20.0)
692           KSPT=KSP20*(THES)**(20.0-TEMP)
693           KMPT=KMP20*(THEM)**(TEMP-20.0)
694           KSST=KSS20*(THEZ)**(TEMP-20.0)
695           KMST=KMS20*(THEA)**(TEMP-20.0)
696           KRT=KR20*(THEE)**(TEMP-20.0)
697           KVT=KV20*(THEE)**(TEMP-20.0)
698           BHT=BH20*(THEE)**(TEMP-20.0)
699           BNT=BN20*(THEE)**(TEMP-20.0)
700           RSM=1.0/((UMT/(1.0+(KNT/(SN*NTIAV))))-BNT)
701           RSA=(1.0-SANOX)*RS
702           TRN=VP/QAV(1)
703           FNS=NONIAV/SBIAV
```

```
704           FACTC=STQAV/(STIAV*QAV(1))
705           FACTN=NTQAV/(NTIAV*QAV(1))
706           CC=(1.0-F)*BHT*YH*RS/(1.0+BHT*(1.0-YH*P*(1.0-F))*RS)
707           FNS=(FNS*(1.0-FBS)+FN*CC)/((1.0-FBS)+P*CC)
708     C
709     C          CALCULATE INTEGRTION STEP LENGTHS
710     C          ---------------------------------
711           DT=1./D
712           DDT=1./DD
713           RDT=DDT/DT
714     C
715     C           RELATE STEP INTERVALS TO THE TIME BASE
716     C           --------------------------------------
717     C
718           II=0
719           KN=M/D
720           KH1=KH+1
721           DO 27 I=1,NL,1
722           JE=I-1
723           IF(JE.EQ.0) GO TO 3
724           KO(I)=KO(I-1)+KN
725           GO TO 4
726         3 KO(I)=KOM
727         4 II=II+1
728           IF (II.EQ.KH1) KO(I)=KO(I)+40
729           IF (II.EQ.KH1) II=1
730           IF (KO(I).GE.2400) KO(I)=KO(I)-2400
731           IF(KO(I).EQ.ICSD) IC=I-1
732           IF(KOM.EQ.ICSD) IC=1
733           IF(KO(I).EQ.ISSD) IS=I
734        27 CONTINUE
735           HK=IS-IC
736           DO 9 J=1,NR,1
737           DO 29 I=1,NL,1
738           WQ(J,I)=0.0
739        29 CONTINUE
740           IF(LRSD(J).EQ.0) GO TO 32
741           DO 28 I=IC,IS,1
742           WQ(J,I)=VP/RS*D/HK*1.0/NRSD
743        28 CONTINUE
744        32 DO 48 I=1,NL,1
745           Q(J+1,I)=Q(J,I)-WQ(J,I)
746           IF(Q(J+1,I).GT.0.00) GO TO 48
747           Q(J+1,I)=0.00
748           WQ(J,I)=Q(J,I)
749        48 CONTINUE
750         9 CONTINUE
751     C
752     C            SET INITIAL CONDITIONS
753     C            ----------------------
754     C
755           DUM=(QSR+Q(NRR,1))/QSR
756           SBPR(1)=SBP(NR,1)*DUM
757           XSR(1)=XS(NR,1)*DUM
758           XAR(1)=XA(NR,1)*DUM
759           XER(1)=XE(NR,1)*DUM
760           XIR(1)=XI(NR,1)*DUM
761           XNR(1)=XN(NR,1)*DUM
762           DO 5 J=1,NR,1
763           WRITE(5,200) SBS(J,1),SBP(J,1),XS(J,1),XA(J,1),XE(J,1),XI(J,1),
764          1XV(J,1),XN(J,1),NO3(J,1),ALK(J,1),SU(J,1),NON(J,1),NH3(J,1)
765         5 CONTINUE
766       200 FORMAT(1H ,5X,13F7.2)
767           DO 15 I=1,D,1
```

```
768         17 J=0
769         19 J=J+1
770       C*****************************************************************
771            IF(NTDN(J,I).EQ.1) CALL UAERO(D,DT,J,FR,FBS,FCS,KVT,KMPT,KSPT,
772           1KMST,KSST,P,NR,YH,BHT,F,KRT,FOE,FN,FOS,FNS,NJ,DDT,UMT,YN,KNT,
773           2RDT,BNT,FACT,LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR,I)
774       C*****************************************************************
775            IF(NTDN(J,I).EQ.0) CALL UANOX(D,DT,J,FR,FBS,FCS,KVT,KMPT,KSPT,
776           1KMST,KSST,P,NR,YH,BHT,F,KRT,FOE,FN,FOS,FNS,NJ,DDT,UMT,YN,KNT,
777           2RDT,BNT,FACT,LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR,I)
778       C*****************************************************************
779            IF(J.EQ.NR) GO TO 20
780            GO TO 19
781         20 CONTINUE
782       C*****************************************************************
783            CALL USETL(NL,J,QSR,I)
784       C*****************************************************************
785         15 CONTINUE
786            DO 26 J=1,NR,1
787            DO 26 I=1,NL
788            JA=I-1
789            IF (JA.EQ.0) JA=D
790            JB=I+1
791            IF (JB.EQ.NLL) JB=2
792            JD=I
793            IF(JD.EQ.NL) JD=1
794            RXS(J,I)=(XS(J,JB)-XS(J,JA))/(DT*2.0)
795            ST(J,I)=SU(J,I)+SBS(J,I)
796            NT(J,I)=NON(J,I)+NU(J,I)+NH3(J,I)
797            OC(J,I)=(1.0-P*YH)*SYNTH(J,JD)/(DT*24.0)
798            ANPOT(J,I)=ANPOT(J,JD)/(DT*24.0)
799            ON(J,I)=4.57*NIT(J,JD)/(DT*24.0)
800            OT(J,I)=OC(J,I)+ON(J,I)
801            AMON(J,I)=AMON(J,JD)/(DT*24.0)
802         26 CONTINUE
803       C
804       C      CALCULATION OF AVERAGE RESULTS FROM DYNAMIC MODEL
805       C      ------------------------------------------------
806       C          EXAMPLE:  XVAV = AVERAGE XV
807       C
808            TRN=0.0
809            SUMXVT=0.0
810            SUMWST=0.0
811            SUMXAM=0.0
812            SUMXEM=0.0
813            SUMXIM=0.0
814            SUMXSM=0.0
815            SUMXNM=0.0
816            SUMODM=0.0
817            SMAPTM=0.0
818            APTMNR=0.0
819            RNO3AV=0.0
820            SUMOCM=0.0
821            SUMONM=0.0
822            SUMOTM=0.0
823            SUMAMM=0.0
824            SUNSWM=0.0
825            TWCOD=0.0
826            TWN=0.0
827            TWALK=0.0
828            EN=0.0
829            ENH3=0.0
830            ENON=0.0
831            ENO3=0.0
```

```
832             EALK=0.0
833             ENT=0.0
834             ECOD=0.0
835             DO 31 J=2,NRR,1
836             SUMQ=0.0
837             DO 30 I=1,D,1
838          30 SUMQ=SUMQ+Q(J,I)
839          31 QAV(J)=SUMQ/D
840             DO 22 J=1,NR,1
841             SUMWS=0.0
842             SUMNSW=0.0
843             SUMNU=0.0
844             SUMXA=0.0
845             SUMXE=0.0
846             SUMXI=0.0
847             SUMSBP=0.0
848             SUMSBS=0.0
849             SUMXV=0.0
850             SUMXS=0.0
851             SUMXN=0.0
852             SUMOC=0.0
853             SUMOD=0.0
854             SUMAPT=0.0
855             SUMON=0.0
856             SUMSU=0.0
857             SUMRXS=0.0
858             SUMNON=0.0
859             SUMNH3=0.0
860             SUMNT=0.0
861             SUMNO3=0.0
862             SUMALK=0.0
863             SUMOT=0.0
864             SUMAM=0.0
865             WCOD=0.0
866             WN=0.0
867             WALK=0.0
868             WNON=0.0
869             DO 21 I=1,D
870             SUMWS=SUMWS+XV(J,I)*WQ(J,I)*DT
871             SUMNSW=SUMNSW+(FN*(XA(J,I)+XE(J,I)+XI(J,I))+FNS*XS(J,I))
872            1*WQ(J,I)*DT
873             IF(J.NE.NR) GO TO 11
874             ECOD=ECOD+Q(J+1,I)*ST(J,I)*DT/QAV(J+1)
875             ESBS=ESBS+Q(J+1,I)*(SBS(J,I))*DT/QAV(J+1)
876             ESU=ESU+Q(J+1,I)*(SU(J,I))*DT/QAV(J+1)
877             EN=EN+Q(J+1,I)*(NT(J,I)+NO3(J,I))*DT/QAV(J+1)
878             ENH3=ENH3+Q(J+1,I)*(NH3(J,I))*DT/QAV(J+1)
879             ENON=ENON+Q(J+1,I)*(NON(J,I))*DT/QAV(J+1)
880             ENO3=ENO3+Q(J+1,I)*(NO3(J,I))*DT/QAV(J+1)
881             EALK=EALK+Q(J+1,I)*(ALK(J,I))*DT/QAV(J+1)
882             ENT=ENT+Q(J+1,I)*(NT(J,I))*DT/QAV(J+1)
883          11 SUMNU=SUMNU+NU(J,I)
884             SUMXA=SUMXA+XA(J,I)
885             SUMXE=SUMXE+XE(J,I)
886             SUMXI=SUMXI+XI(J,I)
887             SUMSBP=SUMSBP+SBP(J,I)
888             SUMSBS=SUMSBS+SBS(J,I)
889             SUMXV=SUMXV+XV(J,I)
890             SUMXN=SUMXN+XN(J,I)
891             SUMXS=SUMXS+XS(J,I)
892             SUMOC=SUMOC+OC(J,I)
893             SUMAPT=SUMAPT+ANPOT(J,I)
894             IF(NTDN(J,I).EQ.1) GO TO 12
895             SUMOD=SUMOD+OC(J,I)
```

```
896          12 SUMON=SUMON+ON(J,I)
897             SUMSU=SUMSU+SU(J,I)
898             SUMRXS=SUMRXS+RXS(J,I)
899             SUMNO3=SUMNO3+NO3(J,I)
900             SUMALK=SUMALK+ALK(J,I)
901             SUMNON=SUMNON+NON(J,I)
902             SUMNH3=SUMNH3+NH3(J,I)
903             SUMNT=SUMNT+NT(J,I)
904             WCOD=WCOD+WQ(J,I)*(ST(J,I)+SBP(J,I))*DT
905             WN=WN+WQ(J,I)*(NT(J,I)+NO3(J,I))*DT
906             WALK=WALK+WQ(J,I)*ALK(J,I)*DT
907             WNON=WNON+WQ(J,I)*NON(J,I)*DT
908             SUMOT=SUMOT+OT(J,I)
909             SUMAM=SUMAM+AMON(J,I)
910          21 CONTINUE
911             NUAV(J)=SUMNU/D
912             XAAV(J)=SUMXA/D
913             XEAV(J)=SUMXE/D
914             XIAV(J)=SUMXI/D
915             SBPAV(J)=SUMSBP/D
916             SBSAV(J)=SUMSBS/D
917             XVAV(J)=SUMXV/D
918             XSAV(J)=SUMXS/D
919             XNAV(J)=SUMXN/D
920             OCAV(J)=SUMOC/D
921             ODAV(J)=SUMOD/D
922             APTAV(J)=SUMAPT/D
923             APTNR(J)=APTAV(J)*24.0*V(J)/QAV(1)
924             RNO3(J)=ODAV(J)*24.0*V(J)/(QAV(1)*2.85)
925             ONAV(J)=SUMON/D
926             SUAV(J)=SUMSU/D
927             RXSAV(J)=SUMRXS/D
928             STAV(J)=SUAV(J)+SBSAV(J)
929             NSWAV(J)=SUMNSW/QAV(1)
930             SUNSWM=SUNSWM+NSWAV(J)
931             OTAV(J)=SUMOT/D
932             AMAV(J)=SUMAM/D
933             NO3AV(J)=SUMNO3/D
934             ALKAV(J)=SUMALK/D
935             NONAV(J)=SUMNON/D
936             NH3AV(J)=SUMNH3/D
937             NTAV(J)=SUMNT/D
938             SUMWST=SUMWST+SUMWS
939             SUMXVT=SUMXVT+XVAV(J)*V(J)
940             SUMXAM=SUMXAM+XAAV(J)*V(J)
941             SUMXEM=SUMXEM+XEAV(J)*V(J)
942             SUMXIM=SUMXIM+XIAV(J)*V(J)
943             SUMXSM=SUMXSM+XSAV(J)*V(J)
944             SUMXNM=SUMXNM+XNAV(J)*V(J)
945             SUMODM=SUMODM+ODAV(J)*V(J)
946             SMAPTM=SMAPTM+APTAV(J)*V(J)
947             APTMNR=APTMNR+APTNR(J)
948             RNO3AV=RNO3AV+RNO3(J)
949             SUMOCM=SUMOCM+OCAV(J)*V(J)
950             SUMONM=SUMONM+ONAV(J)*V(J)
951             SUMOTM=SUMOTM+OTAV(J)*V(J)
952             SUMAMM=SUMAMM+AMAV(J)*V(J)
953             I=NLL
954             Q(J,I)=QAV(J)
955       C*****************************************************************
956             CALL UDUMV(J,I,DUMIF,DUMS,DUMA,DUMB,DUMIR,DUMO,
957            1LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR,
958            1DT,DDT,RDT)
959       C*****************************************************************
```

```
960             RA(J)=24.0*DDT/DUMO
961             RN(J)=V(J)/QAV(J)*24.0
962             TWCOD=TWCOD+WCOD
963             TWN=TWN+WN
964             TWALK=TWALK+WALK
965             TWNON=TWNON+WNON
966             TRN=TRN+RN(J)
967             IF(NTDN(J,I).EQ.1) GO TO 22
968             SUMXVA=SUMXVA+XVAV(J)*V(J)
969          22 CONTINUE
970             RSAV=SUMXVT/SUMWST
971             XAMAV=SUMXAM/VP
972             XEMAV=SUMXEM/VP
973             XIMAV=SUMXIM/VP
974             XSMAV=SUMXSM/VP
975             XVMAV=SUMXVT/VP
976             XNMAV=SUMXNM/VP
977             ODMAV=SUMODM/VP
978             APTMAV=SMAPTM/VP
979             OCMAV=SUMOCM/VP
980             ONMAV=SUMONM/VP
981             OTMAV=SUMOTM/VP
982             AMMAV=SUMAMM/VP
983             CODSI=0.0
984             NTITI=0.0
985             CODSO=0.0
986             NTITO=0.0
987             ALKSI=0.0
988             ALKSO=0.0
989             DO 5000 J=1,NR,1
990             CODSI=CODSI+(XV(J,1)*P+SBP(J,1)+ST(J,1))*V(J)
991             NTITI=NTITI+((XA(J,1)+XE(J,1)+XI(J,I))*FN+XS(J,1)*FNS
992            &+NON(J,1)+NU(J,1)+NH3(J,1)+NO3(J,1))*V(J)
993             CODSO=CODSO+(XV(J,D)*P+SBP(J,D)+ST(J,D))*V(J)
994             NTITO=NTITO+((XA(J,D)+XE(J,D)+XI(J,D))*FN+XS(J,D)*FNS
995            &+NON(J,D)+NU(J,D)+NH3(J,D)+NO3(J,D))*V(J)
996             ALKSI=ALKSI+ALK(J,1)*V(J)
997             ALKSO=ALKSO+ALK(J,D)*V(J)
998       5000  CONTINUE
999       C
1000      C     CHECK MASS BALANCES ON COD,NITROGEN AND ALKALINITY
1001      C  1.  COD
1002      C  -------
1003            TCODI=STQAV+CODSI
1004            TCODO=P*SUMWST+SUMOCM*24.0+TWCOD+ECOD*QAV(NRR)+CODSO
1005            BALC=TCODO*100.0/TCODI
1006      C  2.  NITROGEN
1007      C  ------------
1008            TNTI=NTQAV+NO3QAV+NTITI
1009            TNTO=SUNSWM*QAV(1)+TWN+EN*QAV(NRR)+SUMODM*24/2.85+NTITO
1010            BALN=TNTO*100.0/TNTI
1011      C  3.   ALKALINITY
1012      C  ---------------
1013            TALKI=ALKQAV+ALKSI
1014            TALKO=TWALK+EALK*QAV(NRR)+ALKSO+7.14*SUMONM*24.0/4.57
1015           &-3.57*(SUMODM*24.0/2.86+SUMAMM*24.0)
1016            BALALK=TALKO/TALKI*100.0
1017      C
1018      C
1019      C
1020      C      OUTPUT AND FORMAT STATEMENTS
1021      C      ----------------------------
1022      C
1023            IF(RESULT.EQ.2)GO TO 126
```

```
1024            WRITE(5,98)DATE,XMONTH,YEAR
1025      98    FORMAT(1H0,5X,'DAY OF EXPERIMENT:',1X,A2,1X,'OF',1X,A3,1X,A4)
1026            WRITE(5,201)TEMP,PH,YH,BHT,KVT,YN,THEN,F,FBS,FN,KNT,PHIN,
1027           1THEE,P,FOE,UMT,BNT,FOS,KRT,KSPT,THEZ,KMPT,THEA,THES,
1028           2KMST,KSST,FR,FNS,RS
1029          201 FORMAT(1H1,20X,22('*'),/,1H ,20X,22('*'),/,
1030           11H0,10X,'KINETIC CONSTANTS',/,1H ,10X,17('-'),/,
1031           21H ,5X,'PROCESS OPERATING TEMPERATURE=',F5.1,1X,'DEG. C',/,
1032           31H ,28X,'AND PH=',F5.2,/,1H0,5X,'HETEROTROPHS',28X,'AUTOTROPHS',/,
1033           41H ,5X,12('-'),28X,10('-'),/,1H ,6X,'YH=',F5.3,4X,'BH=',F5.3,4X,
1034           5'KV=',F5.3,8X,'YN=',F5.3,6X,'THEN=',F5.3,/,1H ,7X,'F=',F5.3,3X,
1035           6'FBS=',F5.3,4X,'FN=',F5.3,8X,'KN=',F5.2,6X,'PHIN=',F5.3,/,
1036           75X,'THEE=',F5.3,5X,'P=',F5.3,3X,'FOE=',F5.3,8X,'UM=',F5.3,
1037           28X,'BN=',F5.3,/,
1038           86X,'FOS=',F5.3,4X,'KR=',F5.3,3X,'KSP=',F5.3,6X,'THEZ=',F5.3,/,
1039           16X,'KMP=',F5.3,2X,'THEA=',F5.3,2X,'THES=',F5.3,/,
1040           26X,'KMS=',F5.2,3X,'KSS=',F5.1,/,
1041           27X,'FR=',F5.3,3X,'FNS=',F5.3,/,
1042           11H ,5X,'OPERATING SLUDGE AGE OF PROCESS=',F5.2,1X,'DAYS')
1043            WRITE(5,202)FUP,FUS,SN,UN,QAV(1),STQAV,NTQAV,STIAV,SBIAV,SUIAV,
1044           1XIIAV,NTIAV,NH3IAV,NONIAV,NUIAV,NO3IAV,ALKIAV
1045          202 FORMAT(1H0,10X,'AVERAGE COMPOSITION OF SEWAGE',/,
1046           11H ,10X,29('-'),/,1H0,5X,'SOLID INERT FRACTION OF INFLUENT COD=',
1047           2F5.3,/,1H ,5X,'SOLUBLE INERT FRACTION OF INFLUENT COD=',F5.3,/,
1048           31H ,5X,'AMMONIA TO TKN FRACTION=',F5.3,/,
1049           41H ,5X,'INERT TKN FRACTION=',F5.3,/,1H0,4X,'QAV=',F9.5,
1050           15X,'STQAV=',E13.5,5X,'NTQAV=',E13.5,/,
1051           51H ,5X,'STI=',F7.2,5X,'SBI=',F7.2,4X,'SUI=',F6.2,
1052           64X,'XII=',F6.2,/,1H ,5X,'NTI=',F6.2,4X,'NH3I=',F6.2,
1053           74X,'NONI=',F5.2,5X,'NUI=',F5.2,5X,'NO3I=',F5.2,/,
1054           &4X,'ALKI=',F7.2)
1055            IF(TYPE.EQ.1) GO TO 122
1056            IF(TYPE.EQ.2) GO TO 123
1057            IF(TYPE.EQ.3) GO TO 122
1058          122 WRITE(5,205)VARQ,VARSTI,VARNTI,VNO3I,VARSTL,VARNTL,VRNO3L
1059          205 FORMAT(1H0,10X,'SINE WAVE INFLUENT FLOW AND FEED PATTERN',/,
1060           11H ,10X,40('-'),/,
1061           41H0,10X,'AMPLITUDE OF FLOW WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
1062           51H ,10X,'AMPLITUDE OF COD WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
1063           61H ,10X,'AMPLITUDE OF TKN WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
1064           71H ,10X,'AMPLITUDE OF NO3 WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
1065           81H ,10X,'AMPLITUDE OF COD LOAD WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
1066           81H ,10X,'AMPLITUDE OF TKN LOAD WAVE=',F5.2,4X,'(FRAC OF AVE)',/,
1067           81H ,10X,'AMPLITUDE OF NO3 LOAD WAVE=',F5.2,4X,'(FRAC OF AVE)')
1068          204 FORMAT(1H0,10X,'PROCESS CONFIGURATION DATA',/,1H ,5X,26('-'),/,
1069           11H0,5X,'NUMBER OF TANKS IN SERIES',I2,/,
1070           11H ,5X,'INFLUENT FLOW INTO TANK',I2,/,
1071           11H ,5X,'S-RECYCLE FROM SETTLER TO TANK ',I2,/,
1072           11H ,5X,'A-RECYCLE FROM TANK',I2,1X,'INTO TANK',I2,/,
1073           11H ,5X,'B-RECYCLE FROM TANK',I2,1X,'INTO TANK',I2,/,
1074           11H ,5X,'S RECYCLE RATIO=',F4.1,/,
1075           11H ,5X,'A RECYCLE RATIO=',F4.1,/,
1076           11H ,5X,'B RECYCLE RATIO=',F4.1)
1077            GO TO 124
1078          123   WRITE(5,206)LFP,PQ,BQ,VF
1079          206 FORMAT(1H0,10X,'SQUARE WAVE INFLUENT FLOW AND FEED PATTERN',/,
1080           11H ,10X,42('-'),/,
1081           11H ,10X,'LENGTH OF FEED PERIOD (HRS)=',F5.2,/,
1082           21H ,10X,'PEAK FLOW (L/D)=',F9.5,/,
1083           31H ,10X,'BASE FLOW (L/D)=',F9.5,/,
1084           41H ,10X,'VOLUME OF FEED PER DAY (LITRES)=' F9.5)
1085          124 WRITE(5,203) TRN,VP,ANOXAV,RSAV
1086            WRITE(5,204) NR,LINI,LSRI,LARO,LARI,LBRO,LBRI,SR,AR,BR
1087          203 FORMAT(1H1,10X,21('-'),/,1H ,10X,'DAILY AVERAGE RESULTS',/,
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1088            11H ,10X,21('-'),/,
1089            11H0,5X,'TOTAL HYDRAULIC RETENTION TIME=',F8.3,1X,'HOURS',/,
1090            11H ,5X,'TOTAL VOLUME=',E13.5,1X,'LITRES',/,
1091            11H ,5X,'ANOXIC FRACTION=',F5.3,/,
1092            21H ,5X,'SLUDGE AGE =',F5.2,1X,'DAYS')
1093             WRITE(5,244)TCODI,TCODO,BALC,TNTI,TNTO,BALN,TALKI,TALKO,BALALK
1094          244 FORMAT(1H0,10X,'MASS BALANCES ON COD AND NITROGEN',/,
1095            11H ,10X,33('-'),/,
1096            21H0,5X,'TOTAL COD MASS INPUT=',1X,E13.6,1X,'(MG-COD/D)',/,
1097            21H ,5X,'TOTAL COD MASS OUTPUT=',1X,E13.6,1X,'(MG-COD/D)',/,
1098            31H ,5X,'PERCENTAGE COD RECOVERY=',1X,F7.3,1X,'(%)',/,
1099            21H ,5X,'TOTAL NITROGEN MASS INPUT=',1X,E13.6,1X,'(MG-N/D)',/,
1100            21H ,5X,'TOTAL NITROGEN MASS OUTPUT=',1X,E13.6,1X,'(MG-N/D)',/,
1101            31H ,5X,'PERCENTAGE NITROGEN RECOVERY=',1X,F7.3,1X,'(%)',/,
1102            21H ,5X,'TOTAL ALKALINITY MASS INPUT=',1X,E13.6,1X,'(CACO3/D)',/,
1103            21H ,5X,'TOTAL ALKALINITY MASS OUTPUT=',1X,E13.6,1X,'(CACO3/D)',/,
1104            31H ,5X,'PERCENTAGE ALKALINITY RECOVERY=',1X,F7.3,1X,'(%)')
1105             WRITE(5,300)
1106          300 FORMAT(1H0,30X,'TANK  1',6X,'TANK  2',
1107            26X,'TANK  3',6X,'TANK  4',6X,'TANK  5',6X,'TANK  6',
1108            36X,'MEAN',/,1H ,30X,7('-'),6X,7('-'),6X,7('-'),6X,7('-'),
1109            46X,7('-'),6X,7('-'),6X,4('-'))
1110             WRITE(5,327) (NAME(J),J=1,NR,1)
1111          327 FORMAT(1H ,23X,6A13)
1112             WRITE(5,328)
1113          328 FORMAT(1H ,30X,6('-'),7X,6('-'),7X,6('-'),
1114            17X,6('-'),7X,6('-'),7X,6('-'))
1115             WRITE(5,301) (XAAV(J),J=1,NR,1),XAMAV
1116             WRITE(5,302) (XSAV(J),J=1,NR,1),XSMAV
1117             WRITE(5,303) (XEAV(J),J=1,NR,1),XEMAV
1118             WRITE(5,304) (XIAV(J),J=1,NR,1),XIMAV
1119             WRITE(5,305) (XVAV(J),J=1,NR,1),XVMAV
1120             WRITE(5,319) (XNAV(J),J=1,NR,1),XNMAV
1121             WRITE(5,313) (ODAV(J),J=1,NR,1),ODMAV
1122             WRITE(5,314) (OCAV(J),J=1,NR,1),OCMAV
1123             WRITE(5,315) (ONAV(J),J=1,NR,1),ONMAV
1124             WRITE(5,316) (OTAV(J),J=1,NR,1),OTMAV
1125             WRITE(5,3160) (AMAV(J),J=1,NR,1),AMMAV
1126             WRITE(5,309) (NSWAV(J),J=1,NR,1),SUNSWM
1127             WRITE(5,321) (SBPAV(J),J=1,NR,1)
1128             WRITE(5,320) (SBSAV(J),J=1,NR,1)
1129             WRITE(5,324) (SUAV(J),J=1,NR,1)
1130             WRITE(5,311) (STAV(J),J=1,NR,1)
1131             WRITE(5,306) (NONAV(J),J=1,NR,1)
1132             WRITE(5,310) (NH3AV(J),J=1,NR,1)
1133             WRITE(5,323) (NUAV(J),J=1,NR,1)
1134             WRITE(5,312) (NTAV(J),J=1,NR,1)
1135             WRITE(5,307) (NO3AV(J),J=1,NR,1)
1136             WRITE(5,703) (ALKAV(J),J=1,NR,1)
1137             WRITE(5,308) (RNO3(J),J=1,NR,1),RNO3AV
1138             WRITE(5,326) (APTAV(J),J=1,NR,1),APTMAV
1139             WRITE(5,329) (APTNR(J),J=1,NR,1),APTMNR
1140             WRITE(5,322) (V(J),J=1,NR,1)
1141             WRITE(5,325) (QAV(J),J=1,NRR,1)
1142             WRITE(5,317) (RA(J),J=1,NR,1)
1143             WRITE(5,318) (RN(J),J=1,NR,1)
1144             WRITE(5,3003)(FANOX(J),J=1,NR,1),ANOXAV
1145             WRITE(5,3000)ECOD,ESBS,ESU,EN,ENT,ENH3,ENON,ENO3,EALK
1146         3000  FORMAT(1H0,8X,'AVERAGE EFFLUENT CONCENTRATIONS',/,
1147            &8X,'TOT-COD=',E13.5,/,
1148            &8X,'SBS',E13.5,/,
1149            &8X,'SU',E13.5,/,
1150            &8X,'TOTAL-N=',E13.5,/,
1151            &8X,'TKN',E13.5,/,
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1152          &8X,'NH3',E13.5,/,
1153          &8X,'NON',E13.5,/,
1154          &8X,'NO3',E13.5,/,
1155          &8X,'ALK',E13.5)
1156        301 FORMAT(1H ,8X,'XA    (MG-VSS/L)',2X,7(E13.5))
1157        302 FORMAT(1H ,8X,'XS    (MG-VSS/L)',2X,7(E13.5))
1158        303 FORMAT(1H ,8X,'XE    (MG-VSS/L)',2X,7(E13.5))
1159        304 FORMAT(1H ,8X,'XI    (MG-VSS/L)',2X,7(E13.5))
1160        305 FORMAT(1H ,8X,'XV    (MG-VSS/L)',2X,7(E13.5))
1161        319 FORMAT(1H ,8X,'XN    (MG-VSS/L)',2X,7(E13.5))
1162        313 FORMAT(1H ,8X,'OD   (MG-O/L/HR)',2X,7(E13.5))
1163        314 FORMAT(1H ,8X,'OC   (MG-O/L/HR)',2X,7(E13.5))
1164        315 FORMAT(1H ,8X,'ON   (MG-O/L/HR)',2X,7(E13.5))
1165        316 FORMAT(1H ,8X,'OT   (MG-O/L/HR)',2X,7(E13.5))
1166       3160 FORMAT(1H ,8X,'AM   (MG-N/L/HR)',2X,7(E13.5))
1167        309 FORMAT(1H ,8X,'NSW   (MG-N/L/D)',2X,7(E13.5))
1168        321 FORMAT(1H ,8X,'SBP   (MG-COD/L)',2X,6(E13.5))
1169        320 FORMAT(1H ,8X,'SBS   (MG-COD/L)',2X,6(E13.5))
1170        324 FORMAT(1H ,8X,'SU    (MG-COD/L)',2X,6(E13.5))
1171        311 FORMAT(1H ,8X,'ST    (MG-COD/L)',2X,6(E13.5))
1172        306 FORMAT(1H ,8X,'NON     (MG-N/L)',2X,6(E13.5))
1173        310 FORMAT(1H ,8X,'NH3     (MG-N/L)',2X,6(E13.5))
1174        323 FORMAT(1H ,8X,'NU      (MG-N/L)',2X,6(E13.5))
1175        312 FORMAT(1H ,8X,'NT      (MG-N/L)',2X,6(E13.5))
1176        307 FORMAT(1H ,8X,'NO3     (MG-N/L)',2X,6(E13.5))
1177        703 FORMAT(1H ,8X,'ALK (MG-CACO3/L)',2X,6(E13.5))
1178        326 FORMAT(1H ,8X,'APT (MG-N/L/HR)',2X,7(E13.5))
1179        329 FORMAT(1H ,8X,'APTNR  (MG-N/L)',2X,7(E13.5))
1180        308 FORMAT(1H ,8X,'RNO3   (MG-N/L)',2X,7(E13.5))
1181        322 FORMAT(1H ,8X,'VOL    (LITRES)',2X,6(E13.5))
1182        325 FORMAT(1H ,8X,'FLOW      (L/D)',2X,7(E13.5))
1183        317 FORMAT(1H ,8X,'AHRT    (HOURS)',2X,6(E13.5))
1184        318 FORMAT(1H ,8X,'NHRT    (HOURS)',2X,6(E13.5))
1185       3003  FORMAT(1H ,8X,'ANOX FR   (%)',2X,7(E13.5))
1186            WRITE(CH,'(I1)')NR
1187            IMFT(10:10)=CH
1188            WRITE(5,399) (KO(I),STQ(I),NTQ(I),Q(1,I),SBI(I),STI(I),
1189           1NTI(I),SUI(I),NUI(I),XII(I),NH3I(I),NONI(I),I=1,NL,KH)
1190          399 FORMAT(1H1,10X,'DYNAMIC INPUTS',/,1H ,10X,14('-'),/,
1191           11H ,2X,'TIME',2X,'COD LOAD',2X,'TKN LOAD',4X,'FLOW',7X,'SBI',7X,
1192           2'STI',7X,'NTI',7X,'SUI',7X,'NUI',7X,'XII',6X,'NH3I',6X,'NONI',/,
1193           31H ,2X,4('-'),2X,8('-'),3X,8('-'),4X,4('-'),7X,3('-'),7X,3('-'),
1194           47X,3('-'),7X,3('-'),7X,3('-'),7X,3('-'),6X,4('-'),6X,4('-'),/,
1195           5(1H ,2X,I4,11(E10.4)))
1196            WRITE(5,400)
1197          400 FORMAT(1H1,10X,21('-'),/,1H ,10X,'DAILY DYNAMIC RESULTS',/,
1198           11H ,10X,21('-'),/,
1199           11H0,20X,'TIME',5X,'TANK  1',6X,'TANK  2',
1200           26X,'TANK  3',6X,'TANK  4',6X,'TANK  5',6X,'TANK  6',/,
1201           31H ,20X,4('-'),5X,7('-'),6X,7('-'),6X,7('-'),6X,7('-'),
1202           46X,7('-'),6X,7('-'))
1203            WRITE(5,401)
1204          401 FORMAT(1H0,3X,'XA    (MG-VSS/L)')
1205            WRITE(5,IMFT) (KO(I),(XA(J,I),J=1,NR,1),I=1,NL,KH)
1206            WRITE(5,402)
1207          402 FORMAT(1H0,3X,'XS    (MG-VSS/L)')
1208            WRITE(5,IMFT) (KO(I),(XS(J,I),J=1,NR,1),I=1,NL,KH)
1209            WRITE(5,403)
1210          403 FORMAT(1H0,3X,'XE    (MG-VSS/L)')
1211            WRITE(5,IMFT) (KO(I),(XE(J,I),J=1,NR,1),I=1,NL,KH)
1212            WRITE(5,404)
1213          404 FORMAT(1H0,3X,'XI    (MG-VSS/L)')
1214            WRITE(5,IMFT) (KO(I),(XI(J,I),J=1,NR,1),I=1,NL,KH)
1215            WRITE(5,405)
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1216        405 FORMAT(1H0,3X,'XV    (MG-VSS/L)')
1217            WRITE(5,IMFT) (KO(I),(XV(J,I),J=1,NR,1),I=1,NL,KH)
1218            WRITE(5,419)
1219        419 FORMAT(1H0,3X,'XN    (MG-VSS/L)')
1220            WRITE(5,IMFT) (KO(I),(XN(J,I),J=1,NR,1),I=1,NL,KH)
1221            WRITE(5,407)
1222        407 FORMAT(1H0,3X,'OC  (MG-O/L/HR)')
1223            WRITE(5,IMFT) (KO(I),(OC(J,I),J=1,NR,1),I=1,NL,KH)
1224            WRITE(5,408)
1225        408 FORMAT(1H0,3X,'ON  (MG-O/L/HR)')
1226            WRITE(5,IMFT) (KO(I),(ON(J,I),J=1,NR,1),I=1,NL,KH)
1227            WRITE(5,409)
1228        409 FORMAT(1H0,3X,'OT  (MG-O/L/HR)')
1229            WRITE(5,IMFT) (KO(I),(OT(J,I),J=1,NR,1),I=1,NL,KH)
1230            WRITE(5,4090)
1231       4090 FORMAT(1H0,3X,'AM (MG-N/L/HR)')
1232            WRITE(5,IMFT) (KO(I),(AMON(J,I),J=1,NR,1),I=1,NL,KH)
1233            WRITE(5,417)
1234        417 FORMAT(1H0,3X,'WQ       (L/DAY)')
1235            WRITE(5,IMFT) (KO(I),(WQ(J,I),J=1,NR,1),I=1,NL,KH)
1236            WRITE(5,411)
1237        411 FORMAT(1H0,3X,'SBP  (MG-COD/L)')
1238            WRITE(5,IMFT) (KO(I),(SBP(J,I),J=1,NR,1),I=1,NL,KH)
1239            WRITE(5,418)
1240        418 FORMAT(1H0,3X,'SBS  (MG-COD/L)')
1241            WRITE(5,IMFT) (KO(I),(SBS(J,I),J=1,NR,1),I=1,NL,KH)
1242            WRITE(5,420)
1243        420 FORMAT(1H0,3X,'SU   (MG-COD/L)')
1244            WRITE(5,IMFT) (KO(I),(SU(J,I),J=1,NR,1),I=1,NL,KH)
1245            WRITE(5,412)
1246        412 FORMAT(1H0,3X,'ST   (MG-COD/L)')
1247            WRITE(5,IMFT) (KO(I),(ST(J,I),J=1,NR,1),I=1,NL,KH)
1248            WRITE(5,413)
1249        413 FORMAT(1H0,3X,'NON     (MG-N/L)')
1250            WRITE(5,IMFT) (KO(I),(NON(J,I),J=1,NR,1),I=1,NL,KH)
1251            WRITE(5,421)
1252        421 FORMAT(1H0,3X,'NU      (MG-N/L)')
1253            WRITE(5,IMFT) (KO(I),(NU(J,I),J=1,NR,1),I=1,NL,KH)
1254            WRITE(5,415)
1255        415 FORMAT(1H0,3X,'NH3     (MG-N/L)')
1256            WRITE(5,IMFT) (KO(I),(NH3(J,I),J=1,NR,1),I=1,NL,KH)
1257            WRITE(5,414)
1258        414 FORMAT(1H0,3X,'NT      (MG-N/L)')
1259            WRITE(5,IMFT) (KO(I),(NT(J,I),J=1,NR,1),I=1,NL,KH)
1260            WRITE(5,422)
1261        422 FORMAT(1H0,3X,'APT (MG-N/L/HR)')
1262            WRITE(5,IMFT) (KO(I),(ANPOT(J,I),J=1,NR,1),I=1,NL,KH)
1263            WRITE(5,416)
1264        416 FORMAT(1H0,3X,'NO3     (MG-N/L)')
1265            WRITE(5,IMFT) (KO(I),(NO3(J,I),J=1,NR,1),I=1,NL,KH)
1266            WRITE(5,461)
1267        461 FORMAT(1H0,3X,'ALK     (MG-CACO3/L)')
1268            WRITE(5,IMFT) (KO(I),(ALK(J,I),J=1,NR,1),I=1,NL,KH)
1269            IF(RESULT.NE.0) GO TO 127
1270       126  WRITE(18,522)ECOD,ENT,ENH3,ENO3,EALK
1271            WRITE(18,522)KOM,D,INIT(1),ANOX(1),AROB(1),IFREQ,NDH
1272       522  FORMAT()
1273            WRITE(18,45)(OT(1,I),XV(1,I),ST(1,I),NT(1,I),NH3(1,I),NO3(1,I),
1274           &ALK(1,I),I=1,NDH)
1275            WRITE(18,522) START,END
1276       45   FORMAT(7E13.5)
1277            ENDFILE 18
1278       127  STOP
1279            END
```

```
      C*****************************************************************
            SUBROUTINE UAERO(D,DT,J,FR, FBS,FCS,KVT,KMPT,KSPT,KMST,KSST,
           1P,NR,YH,BHT,F,KRT,FOE,FN,FOS,FNS,NJ,DDT,UMT,YN,KNT,RDT,BNT,
           2FACT,LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR,I)
      C*****************************************************************
      C              THIS SUBROUTINE CALCULATES THE DYNAMIC RESPONSE OF A
      C                REACTOR IN A SERIES UNDER AEROBIC CONDITIONS
      C*****************************************************************
            PARAMETER NE=3
            PARAMETER NEE=4
            PARAMETER ND=241
            PARAMETER NDD=242
            INTEGER D
            DOUBLE PRECISION DT,DDT,RDT
            COMMON/EXTC/SBS(NE,ND),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
           1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,ND),NH3(NE,ND),
           2NO3(NE,ND),SBP(NE,ND),ALK(NE,ND)
            COMMON/BLOCKC/Q(NEE,NDD),V(NE),SBI(ND),SUI(ND),NIT(NE,ND),
           1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),ALKI(ND),
           2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(ND),SYNTH(NE,ND),QAV(NEE),
           3ANPOT(NE,ND),AMON(NE,ND)
            REAL KVT,KMPT,KSPT,KMST,KSST,KRT,KNT
            REAL NUI,NONI,NH3I,NO3I,NIT
            REAL NU,NON,NH3,NO3
            REAL NH3T,NITT,NNIT,NO3T
      C*****************************************************************
            CALL UDUMV(J,I,DUMIF,DUMS,DUMA,DUMB,DUMIR,DUMO,
           1LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR,
           1DT,DDT,RDT)
      C*****************************************************************
            K=J-1
            IF(K.EQ.0) K=1
            SCER=P*(1.0-F)*BHT*XA(J,I)*DDT
            SCERN=FN*SCER/P
            CVNON=KRT*XA(J,I)*NON(J,I)*DDT
            SBST=SBS(J,I)
            SBST=SBS(J,I)
            NH3T=NH3(J,I)
            NO3T=NO3(J,I)
            XNT=XN(J,I)
            SCVO=0.00
            SCIS=0.00
            NNIT=0.0
            ANPOTS=0.0
            DO 212 IJ=1,NJ,1
            SCIST=KMST*SBST/(KSST+SBST)*XA(J,I)*DDT
            SCVOT=KMPT*XS(J,I)/(KSPT*XA(J,I)+XS(J,I)*P)*XA(J,I)*DDT
            SYNTHT=SCVOT*P+SCIST
            NITT=(UMT/YN)*NH3T/(KNT+NH3T)*XNT*DDT
            SBST=SBST+DUMIF*FBS*SBI(I)-SCIST
           1+DUMS*SBS(NR,I)+DUMA*SBS(LARO,I)-DUMO*SBST
           1+DUMB*SBS(LBRO,I)+DUMIR*SBS(K,I)
            IF(SBST.LE.0.0) SBST=0.0
            TNH3T=NH3T+DUMIF*NH3I(I)+CVNON-NITT
           1+DUMS*NH3(NR,I)+DUMA*NH3(LARO,I)-DUMO*NH3T
           1+DUMB*NH3(LBRO,I)+DUMIR*NH3(K,I)
           1+(1.0-FOE)*SCERN-(1.0-FOS)*FN*YH*SYNTHT
            IF(TNH3T.GT.0.0) GO TO 433
            NH3T=0.0
            NO3T=NO3T+DUMIF*NO3I(I)+TNH3T
           1+DUMS*NO3(NR,I)+DUMA*NO3(LARO,I)-DUMO*NO3T
           1+DUMB*NO3(LBRO,I)+DUMIR*NO3(K,I)
            GO TO 444
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      433 NH3T=TNH3T
          NO3T=NO3T+DUMIF*NO3I(I)+NITT
         1+DUMS*NO3(NR,I)+DUMA*NO3(LARO,I)-DUMO*NO3T
         1+DUMB*NO3(LBRO,I)+DUMIR*NO3(K,I)
      444 XNT=XNT+YN*NITT-BHT*XNT*DDT
         1+DUMS*XNR(I)+DUMA*XN(LARO,I)-DUMO*XNT
         1+DUMB*XN(LBRO,I)+DUMIR*XN(K,I)
          SCVO=SCVO+SCVOT
          SCIS=SCIS+SCIST
          NNIT=NNIT+NITT
      212 CONTINUE
          SYNTH(J,I)=SCVO*P+SCIS
          NIT(J,I)=NNIT
          ANPOT(J,I)=ANPOTS
          SBS(J,I+1)=SBST
          NH3(J,I+1)=NH3T
          NO3(J,I+1)=NO3T
          XN(J,I+1)=XNT
          DUMIF=DUMIF/RDT
          DUMIR=DUMIR/RDT
          DUMA=DUMA/RDT
          DUMB=DUMB/RDT
          DUMS=DUMS/RDT
          DUMO=DUMO/RDT
          BRAK=FR-(XS(J,I)/(XA(J,I)))
          IF(BRAK.GT.0.00) GO TO 40
          BRAK=0.00
          XS(J,I)=FR*(XA(J,I))
       40 XV(J,I)=XS(J,I)+XA(J,I)+XE(J,I)+XI(J,I)
          SCIP=DT*KVT*BRAK*SBP(J,I)*XA(J,I)
          SBP(J,I+1)=SBP(J,I)+DUMIF*(1.0-FBS)*SBI(I)-SCIP
         1+DUMS*SBPR(I)+DUMA*SBP(LARO,I)-DUMO*SBP(J,I)
         1+DUMB*SBP(LBRO,I)+DUMIR*SBP(K,I)
         2+(1.0-FCS)*SCER/RDT
          IF(SBP(J,I+1).LT.0.0) SBP(J,I+1)=0.0
          XS(J,I+1)=XS(J,I)+SCIP/P-SCVO
         1+DUMS*XSR(I)+DUMA*XS(LARO,I)-DUMO*XS(J,I)
         1+DUMB*XS(LBRO,I)+DUMIR*XS(K,I)
          IF(XS(J,I+1).LT.0.0) XS(J,I+1)=0.0
          SU(J,I+1)=SU(J,I)+DUMIF*SUI(I)
         1+DUMS*SU(NR,I)+DUMA*SU(LARO,I)-DUMO*SU(J,I)
         1+DUMB*SU(LBRO,I)+DUMIR*SU(K,I)
          NU(J,I+1)=NU(J,I)+DUMIF*NUI(I)
         1+DUMS*NU(NR,I)+DUMA*NU(LARO,I)-DUMO*NU(J,I)
         1+DUMB*NU(LBRO,I)+DUMIR*NU(K,I)
          XA(J,I+1)=XA(J,I)+YH*SYNTH(J,I)-BHT*XA(J,I)*DT
         1+DUMS*XAR(I)+DUMA*XA(LARO,I)-DUMO*XA(J,I)
         1+DUMB*XA(LBRO,I)+DUMIR*XA(K,I)
          XE(J,I+1)=XE(J,I)+F*BHT*XA(J,I)*DT
         1+DUMS*XER(I)+DUMA*XE(LARO,I)-DUMO*XE(J,I)
         1+DUMB*XE(LBRO,I)+DUMIR*XE(K,I)
          XI(J,I+1)=XI(J,I)+DUMIF*XII(I)
         1+DUMS*XIR(I)+DUMA*XI(LARO,I)-DUMO*XI(J,I)
         1+DUMB*XI(LBRO,I)+DUMIR*XI(K,I)
          NON(J,I+1)=NON(J,I)+DUMIF*NONI(I)-CVNON/RDT
         1+DUMS*NON(NR,I)+DUMA*NON(LARO,I)-DUMO*NON(J,I)
         1+DUMB*NON(LBRO,I)+DUMIR*NON(K,I)
         2+FOE*SCERN/RDT-FOS*FN*YH*SYNTH(J,I)
         3-FNS*(SCIP/P-SCVO)
          AMON(J,I)=(CVNON/RDT+(1.0-FOE)*SCERN/RDT)
         1-(1.0-FOS)*FN*YH*SYNTH(J,I)
          ALK(J,I+1)=ALK(J,I)+DUMIF*ALKI(I)
         1+DUMS*ALK(NR,I)+DUMA*ALK(LARO,I)-DUMO*ALK(J,I)
         1+DUMB*ALK(LBRO,I)+DUMIR*ALK(K,I)
```

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128             1-7.14*NIT(J,I)+3.57*AMON(J,I)
129              XV(J,I+1)=XS(J,I+1)+XA(J,I+1)+XE(J,I+1)+XI(J,I+1)
130              RETURN
131              END
```

```
      C*************************************************************
            SUBROUTINE UANOX(D,DT,J,FR,FBS,FCS,KVT,KMPT,KSPT,KMST,KSST,
           1P,NR,YH,BHT,F,KRT,FOE,FN,FOS,FNS,NJ,DDT,UMT,YN,KNT,RDT,BNT,
           2FACT,LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR,I)
      C*************************************************************
      C             THIS SUBROUTINE CALCULATES THE DYNAMIC RESPONSE OF A
      C               REACTOR IN A SERIES UNDER ANOXIC CONDITIONS
      C*************************************************************
            PARAMETER NE=3
            PARAMETER NEE=4
            PARAMETER ND=241
            PARAMETER NDD=242
            INTEGER D
            DOUBLE PRECISION DT,DDT,RDT
            COMMON/EXTC/SBS(NE,ND),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
           1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,ND),NH3(NE,ND),
           2NO3(NE,ND),SBP(NE,ND),ALK(NE,ND)
            COMMON/BLOCKC/Q(NEE,NDD),V(NE),SBI(ND),SUI(ND),NIT(NE,ND),
           1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),ALKI(ND),
           2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(ND),SYNTH(NE,ND),QAV(NEE),
           3ANPOT(NE,ND),AMON(NE,ND)
            REAL KVT,KMPT,KSPT,KMST,KSST,KRT,KNT
            REAL NUI,NONI,NH3I,NO3I,NIT
            REAL NU,NON,NH3,NO3
            REAL NH3T,NITT,NNIT,NO3T
            RNCOD=2.85/(1.0-P*YH)
      C*************************************************************
            CALL UDUMV(J,I,DUMIF,DUMS,DUMA,DUMB,DUMIR,DUMO,
           1LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR,
           1DT,DDT,RDT)
      C*************************************************************
            K=J-1
            IF(K.EQ.0) K=1
            SCER=P*(1.0-F)*BHT*XA(J,I)*DDT
            SCERN=FN*SCER/P
            CVNON=KRT*FACT*XA(J,I)*NON(J,I)*DDT
            SCVOD=KMPT*XS(J,I)/(KSPT*XA(J,I)+XS(J,I)*P)*FACT*XA(J,I)*DDT
            SCVO=0.00
            SCIS=0.00
            NNIT=0.00
            ANPOTS=0.00
            SBST=SBS(J,I)
            SBST=SBS(J,I)
            NH3T=NH3(J,I)
            NO3T=NO3(J,I)
            XNT=XN(J,I)
            DO 213 IJ=1,NJ,1
            SCIST=KMST*SBST/(KSST+SBST)*FACT*XA(J,I)*DDT
            SCVOT=KMPT*XS(J,I)/(KSPT*XA(J,I)+XS(J,I)*P)*FACT*XA(J,I)*DDT
            SYNTHT=SCVOT*P+SCIST
            DENCAP=SYNTHT/RNCOD
            DENIT=DENCAP
            RDEN=SCIST/SYNTHT
            NITT=0.0
            ANPOTT=0.00
            IF((NO3T-DENIT).GT.0.00) GO TO 13
            DENIT=NO3T
            SYNTHT=DENIT*RNCOD
            SCIST=SYNTHT*RDEN
            SCVOT=SYNTHT*(1.0-RDEN)/P
            ANPOTT=DENCAP-DENIT
         13 CONTINUE
            SCVO=SCVO+SCVOT
```

```
      SCIS=SCIS+SCIST
      ANPOTS=ANPOTS+ANPOTT
      SBST=SBST+DUMIF*FBS*SBI(I)-SCIST
     1+DUMS*SBS(NR,I)+DUMA*SBS(LARO,I)-DUMO*SBST
     1+DUMB*SBS(LBRO,I)+DUMIR*SBS(K,I)
      IF(SBST.LE.0.0) SBST=0.0
      NITT=0.00
      TNH3T=NH3T+DUMIF*NH3I(I)+CVNON
     1+DUMS*NH3(NR,I)+DUMA*NH3(LARO,I)-DUMO*NH3T
     1+DUMB*NH3(LBRO,I)+DUMIR*NH3(K,I)
     1+(1.0-FOE)*SCERN-(1.0-FOS)*FN*YH*SYNTHT
      IF(TNH3T.GT.0.0) GO TO 43
      NH3T=0.0
      NO3T=NO3T+DUMIF*NO3I(I)+NITT-DENIT+TNH3T
     1+DUMS*NO3(NR,I)+DUMA*NO3(LARO,I)-DUMO*NO3T
     1+DUMB*NO3(LBRO,I)+DUMIR*NO3(K,I)
      IF(NO3T.LT.0.00) NO3T=0.00
      GO TO 44
   43 NH3T=TNH3T
      NO3T=NO3T+DUMIF*NO3I(I)+NITT-DENIT
     1+DUMS*NO3(NR,I)+DUMA*NO3(LARO,I)-DUMO*NO3T
     1+DUMB*NO3(LBRO,I)+DUMIR*NO3(K,I)
   44 XNT=XNT+YN*NITT-BHT*XNT*DDT
     1+DUMS*XNR(I)+DUMA*XN(LARO,I)-DUMO*XNT
     1+DUMB*XN(LBRO,I)+DUMIR*XN(K,I)
  213 CONTINUE
       SYNTH(J,I)=SCVO*P+SCIS
      NIT(J,I)=NNIT
      ANPOT(J,I)=ANPOTS
      SBS(J,I+1)=SBST
      NH3(J,I+1)=NH3T
      NO3(J,I+1)=NO3T
      XN(J,I+1)=XNT
      DUMIF=DUMIF/RDT
      DUMIR=DUMIR/RDT
      DUMA=DUMA/RDT
      DUMB=DUMB/RDT
      DUMS=DUMS/RDT
      DUMO=DUMO/RDT
      BRAK=FR-(XS(J,I)/(XA(J,I)))
      IF(BRAK.GT.0.00) GO TO 40
      BRAK=0.00
      XS(J,I)=FR*(XA(J,I))
   40 XV(J,I)=XS(J,I)+XA(J,I)+XE(J,I)+XI(J,I)
      SCIP=DT*KVT*BRAK*SBP(J,I)*XA(J,I)
      SBP(J,I+1)=SBP(J,I)+DUMIF*(1.0-FBS)*SBI(I)-SCIP
     1+DUMS*SBPR(I)+DUMA*SBP(LARO,I)-DUMO*SBP(J,I)
     1+DUMB*SBP(LBRO,I)+DUMIR*SBP(K,I)
     2+(1.0-FCS)*SCER/RDT
      IF(SBP(J,I+1).LT.0.0) SBP(J,I+1)=0.0
      XS(J,I+1)=XS(J,I)+SCIP/P-SCVO
     1+DUMS*XSR(I)+DUMA*XS(LARO,I)-DUMO*XS(J,I)
     1+DUMB*XS(LBRO,I)+DUMIR*XS(K,I)
      IF(XS(J,I+1).LT.0.0) XS(J,I+1)=0.0
      SU(J,I+1)=SU(J,I)+DUMIF*SUI(I)
     1+DUMS*SU(NR,I)+DUMA*SU(LARO,I)-DUMO*SU(J,I)
     1+DUMB*SU(LBRO,I)+DUMIR*SU(K,I)
      NU(J,I+1)=NU(J,I)+DUMIF*NUI(I)
     1+DUMS*NU(NR,I)+DUMA*NU(LARO,I)-DUMO*NU(J,I)
     1+DUMB*NU(LBRO,I)+DUMIR*NU(K,I)
      XA(J,I+1)=XA(J,I)+YH*SYNTH(J,I)-BHT*XA(J,I)*DT
     1+DUMS*XAR(I)+DUMA*XA(LARO,I)-DUMO*XA(J,I)
     1+DUMB*XA(LBRO,I)+DUMIR*XA(K,I)
      XE(J,I+1)=XE(J,I)+F*BHT*XA(J,I)*DT
```

```
     1+DUMS*XER(I)+DUMA*XE(LARO,I)-DUMO*XE(J,I)
     1+DUMB*XE(LBRO,I)+DUMIR*XE(K,I)
      XI(J,I+1)=XI(J,I)+DUMIF*XII(I)
     1+DUMS*XIR(I)+DUMA*XI(LARO,I)-DUMO*XI(J,I)
     1+DUMB*XI(LBRO,I)+DUMIR*XI(K,I)
      NON(J,I+1)=NON(J,I)+DUMIF*NONI(I)-CVNON/RDT
     1+DUMS*NON(NR,1)+DUMA*NON(LARO,I)-DUMO*NON(J,I)
     1+DUMB*NON(LBRO,I)+DUMIR*NON(K,I)
     2+FOE*SCERN/RDT-FOS*FN*YH*SYNTH(J,I)
     3-FNS*(SCIP/P-SCVO)
      AMON(J,I)=(CVNON/RDT+(1.0-FOE)*SCERN/RDT)
     1-(1.0-FOS)*FN*YH*SYNTH(J,I)
      ALK(J,I+1)=ALK(J,I)+DUMIF*ALKI(I)
     1+DUMS*ALK(NR,I)+DUMA*ALK(LARO,I)-DUMO*ALK(J,I)
     1+DUMB*ALK(LBRO,I)+DUMIR*ALK(K,I)
     1+3.57*(SYNTH(J,I)/RNCOD+AMON(J,I))
      XV(J,I+1)=XS(J,I+1)+XA(J,I+1)+XE(J,I+1)+XI(J,I+1)
      RETURN
      END
```

```
1       C*************************************************************************
2             SUBROUTINE USETL(NL,J,QSR,I)
3       C*************************************************************************
4       C               THIS SUBROUTINE CALCULATES THE DYNAMIC RESPONSE OF THE
5       C                 SETTLING TANK
6       C*************************************************************************
7             PARAMETER NE=3
8             PARAMETER NEE=4
9             PARAMETER ND=241
10            PARAMETER NDD=242
11            COMMON/EXTC/SBS(NE,ND),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
12           1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,ND),NH3(NE,ND),
13           2NO3(NE,ND),SBP(NE,ND),ALK(NE,ND)
14            COMMON/BLOCKC/Q(NEE,NDD),V(NE),SBI(ND),SUI(ND),NIT(NE,ND),
15           1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),ALKI(ND),
16           2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(ND),SYNTH(NE,ND),QAV(NEE),
17           3ANPOT(NE,ND),AMON(NE,ND)
18            REAL NUI,NON1,NH3I,NO3I,NIT
19            REAL NU,NON,NH3,NO3
20            DUM=(QSR+Q(J+1,I))/QSR
21            XAR(I+1)=XA(J,I+1)*DUM
22            XSR(I+1)=XS(J,I+1)*DUM
23            XER(I+1)=XE(J,I+1)*DUM
24            XIR(I+1)=XI(J,I+1)*DUM
25            SBPR(I+1)=SBP(J,I+1)*DUM
26            XNR(I+1)=XN(J,I+1)*DUM
27            RETURN
28            END
```

```
1       C*************************************************************************
2             SUBROUTINE UDUMV(J,I,DUMIF,DUMS,DUMA,DUMB,DUMIR,DUMO,
3            1LINI,LSRI,LARI,LARO,LBRI,LBRO,QSR,QAR,QBR,
4            1DT,DDT,RDT)
5       C*************************************************************************
6       C              THIS SUBROUTINE CALCULATES THE DUMMY VALUES
7       C              FROM THE PROCESS CONFIGURATION INPUT DATA
8       C*************************************************************************
9             PARAMETER NE=3
10            PARAMETER NEE=4
11            PARAMETER ND=241
12            PARAMETER NDD=242
13            INTEGER D
14            DOUBLE PRECISION DT,DDT,RDT
15            COMMON/EXTC/SBS(NE,ND),SU(NE,ND),XA(NE,ND),XE(NE,ND),XI(NE,ND),
16           1XV(NE,ND),XS(NE,ND),NU(NE,ND),NON(NE,ND),XN(NE,ND),NH3(NE,ND),
17           2NO3(NE,ND),SBP(NE,ND),ALK(NE,ND)
18            COMMON/BLOCKC/Q(NEE,NDD),V(NE),SBI(ND),SUI(ND),NIT(NE,ND),
19           1NUI(ND),XII(ND),NONI(ND),NH3I(ND),NO3I(ND),SBPR(ND),ALKI(ND),
20           2XAR(ND),XSR(ND),XER(ND),XIR(ND),XNR(ND),SYNTH(NE,ND),QAV(NEE),
21           3ANPOT(NE,ND),AMON(NE,ND)
22            DUMIF=0.0
23            IF(J.EQ.LINI) DUMIF=DDT*Q(J,I)/V(J)
24            DUMS=0.0
25            IF(J.EQ.LSRI) DUMS=DDT*QSR/V(J)
26            DUMA=0.0
27            IF(J.EQ.LARI.AND.J.LT.LARO) DUMA=DDT*QAR/V(J)
28            DUMB=0.0
29            IF(J.EQ.LBRI.AND.J.LT.LBRO) DUMB=DDT*QBR/V(J)
30            IF(J.EQ.1) GO TO 11
31            IF(J.LE.LINI.AND.J.GT.LSRI) DUMIR=DDT*QSR/V(J)
32            IF(J.LE.LINI.AND.J.LE.LSRI.AND.J.GT.LBRI.AND.J.LE.LBRO)
33           1DUMIR=DDT*QBR/V(J)
34            IF(J.LE.LINI.AND.J.LE.LSRI.AND.J.GT.LARI.AND.J.LE.LARO)
35           1DUMIR=DDT*QAR/V(J)
36            IF(J.LE.LINI.AND.J.LE.LSRI.AND.J.GT.LARI.AND.J.LE.LARO.
37           1AND.J.GT.LBRI.AND.J.LE.LBRO) DUMIR=DDT*(QAR+QBR)/V(J)
38            IF(J.LE.LINI.AND.J.GT.LSRI.AND.J.GT.LARI.AND.J.LE.LARO)
39           1DUMIR=DDT*(QSR+QAR)/V(J)
40            IF(J.LE.LINI.AND.J.GT.LSRI.AND.J.GT.LBRI.AND.J.LE.LBRO)
41           1DUMIR=DDT*(QSR+QBR)/V(J)
42            IF(J.LE.LINI.AND.J.GT.LSRI.AND.J.GT.LARI.AND.J.LE.LARO.
43           1AND.J.GT.LBRI.AND.J.LE.LBRO) DUMIR=DDT*(QSR+QAR+QBR)/V(J)
44            IF(J.GT.LINI.AND.J.GT.LSRI) DUMIR=DDT*(Q(J,I)+QSR)/V(J)
45            IF(J.GT.LINI.AND.J.LE.LSRI.AND.J.GT.LBRI.AND.J.LE.LBRO)
46           1DUMIR=DDT*(Q(J,I)+QBR)/V(J)
47            IF(J.GT.LINI.AND.J.LE.LSRI.AND.J.GT.LARI.AND.J.LE.LARO)
48           1DUMIR=DDT*(Q(J,I)+QAR)/V(J)
49            IF(J.GT.LINI.AND.J.GT.LSRI.AND.J.GT.LARI.AND.J.LE.LARO)
50           1DUMIR=DDT*(Q(J,I)+QAR+QSR)/V(J)
51            IF(J.GT.LINI.AND.J.GT.LSRI.AND.J.GT.LBRI.AND.J.LE.LBRO)
52           1DUMIR=DDT*(Q(J,I)+QBR+QSR)/V(J)
53            IF(J.GT.LINI.AND.J.GT.LSRI.AND.J.GT.LARI.AND.J.LE.LARO.
54           1AND.J.GT.LBRI.AND.J.LE.LBRO) DUMIR=DDT*(Q(J,I)+QSR+QAR+QBR)/V(J)
55         11 CONTINUE
56            IF(J.EQ.1) DUMIR=0.0
57            DUMO=DUMIF+DUMIR+DUMS+DUMA+DUMB
58            RETURN
59            END
```

PROGRAM A.3

```
1       C**********************************************************************
2       C       THIS PROGRAMME CAN BE USED FOR PLOTTING OF BOTH
3       C       SIMULATED AND EXPERIMENTAL DATA OF ALL THE MEASURABLE
4       C       VARIABLES IN AN ACTIVATED SLUDGE PROCESS VIZ.:
5       C       1) OXYGEN UPTAKE RATE (OT IN MG/L/H)
6       C       2) FILTERED COD CONCENTRATION (COD IN  MG COD/L)
7       C       3) VSS CONCENTRATION ( VSS IN  MG VSS/L)
8       C       4) FILTERED TKN CONCENTRATION (TKN IN  MG TKN/L)
9       C       5) AMMONIA CONCENTRATION (NH3-N IN  MG NH3-N/L)
10      C       6) NITRATE CONCENTRATION (NO3-N IN  MG NO3-N/L)
11      C       7) ALKALINITY (ALK IN MG CACO3/L)
12      C       THESE PLOTS ALLOW A GRAPHICAL COMPARISON BETWEEN THE
13      C       EXPERIMENTAL AND SIMULATED PROCESS RESPONSE FOR ALL
14      C       THE MEASURABLE VARIABLES.
15      C
16      C
17      C       THE SIMULATED VALUES OF THE VARIABLES ARE READ FROM A
18      C       DATA FILE GENERATED BY THE DYNAMIC STEADY STATE OR THE
19      C       UNSTEADY STATE PROGRAMS. THE EXPERIMENTAL VALUES ARE
20      C       ENTERED AS DATA.
21      C
22      C
23      C       THE SUBROUTINE NAXIS IS WRITTEN BY PROF H.O.BUHR
24      C       AND IS UTILIZED FOR SPECIFYING THE DIVISION OF THE
25      C       Y- AND X-AXIS. THE OTHER SUBROUTINES CALLED IN THIS
26      C       PROGRAM ARE PART OF THE GENERAL DISPLAY PACKAGE UNIT
27      C       (G.D.P.) AVAILABLE AT THE UNIVERSITY OF CAPE TOWN.
28      C**********************************************************************
29      C       THE NOMENCLATURE OF THE SIMULATED VARIABLES IS EXPLAINED
30      C       IN THE PROGRAM FOR UNSTEADY STATE(H.UNST).
31      C       FOR EXPERIMENTAL VALUES:
32      C       PREFIX T REFERS TO THE TIME OF EXPERIMENTAL VALUE
33      C       PREFIX P REFERS TO THE EXPERIMENTAL VALUE OF THE VARIABLE
34      C       PREFIX N REFERS TO THE NUMBER OF EXPERIMENTAL DETERMI-
35      C       NATIONS OF THE VARIABLE IN THE SET OF DATA
36      C**********************************************************************
37      C       NAMES BEGINNING WITH Y REFER TO THE ORDINATES OF THE DIAGRAMS
38      C       YAX =LENGTH OF THE Y-AXIS
39      C       YDOT=LENGTH OF INTERRUPTED LINE INDICATING ANOXIC PERIODS
40      C       Y1,Y2,Y3,Y4,Y5 AND YPLUS INDICATE ORDINATES FOR TEXT
41      C       YSTUK=NUMBER OF SUBDIVISIONS OF THE Y-AXIS
42      C       XSTUK=NUMBER OF SUBDIVISIONS OF THE X-AXIS
43      C       SIZE=SIZE OF EXPERIMENTAL POINTS (IN MM)
44      C       NDEL REFERS TO THE NUMBER OF UNITS PER CM OF ORDINATE
45      C       NFIRST REFERS TO THE STARTING VALUE OF THE VARIABLES
46      C       OEQ REFERS TO EQUIVALENT OXYGEN UPTAKE RATE
47      C       (I.E. DENITRIFICATION RATE*2,86)
48              PARAMETER ND=30
49              PARAMETER NE=244
50              INTEGER D
51              REAL NT(NE),NH3(NE),NO3(NE)
52              DIMENSION T(NE),OT(NE),XV(NE),ST(NE),ALK(NE),TIME(ND),TI(NE)
53              DIMENSION STXV(NE),STST(NE),STNT(NE),STNH3(NE),TOEQ(ND),POEQ(ND)
54              DIMENSION TOT(ND),TXV(ND),TCOD(ND),TTKN(ND),TNH3(ND),TNO3(ND),
55             &TALK(ND)
56              DIMENSION POT(ND),PXV(ND),PCOD(ND),PTKN(ND),PNH3(ND),PNO3(ND),
57             &PALK(ND)
58      C       READ IN SIMULATED DATA
59              READ(18,35)ECOD,ETKN,ENH3,ENO3,EALK
60              WRITE(5,35)ECOD,ETKN,ENH3,ENO3,EALK
61              READ(18,35)KOM,D,INIT,ANOX,AROB,IFREQ,NDH
62              WRITE(5,35)KOM,D,INIT,ANOX,AROB,IFREQ,NDH
63              NFIRST=NDH+1
```

```
128             TOT(I)=(TOT(I)-T(NFIRST))/T(NDEL)
129             POT(I)=(POT(I)-OT(NFIRST))/OT(NDEL)
130       65    CONTINUE
131             DO 56 I=1,K,1
132             TOEQ(I)=(TOEQ(I)-T(NFIRST))/T(NDEL)
133             POEQ(I)=(POEQ(I)-OT(NFIRST))/OT(NDEL)
134       56    CONTINUE
135             DO 75 I=1,NXV,1
136             TXV(I)=(TXV(I)-T(NFIRST))/T(NDEL)
137             PXV(I)=(PXV(I)-XV(NFIRST))/XV(NDEL)
138       75    CONTINUE
139             DO 85 I=1,NCOD,1
140             TCOD(I)=(TCOD(I)-T(NFIRST))/T(NDEL)
141             PCOD(I)=(PCOD(I)-ST(NFIRST))/ST(NDEL)
142       85    CONTINUE
143             DO 95 I=1,NTKN,1
144             TTKN(I)=(TTKN(I)-T(NFIRST))/T(NDEL)
145             PTKN(I)=(PTKN(I)-NT(NFIRST))/NT(NDEL)
146       95    CONTINUE
147             DO 105 I=1,NNH3,1
148             TNH3(I)=(TNH3(I)-T(NFIRST))/T(NDEL)
149             PNH3(I)=(PNH3(I)-NH3(NFIRST))/NH3(NDEL)
150       105   CONTINUE
151             DO 115 I=1,NNO3,1
152             TNO3(I)=(TNO3(I)-T(NFIRST))/T(NDEL)
153             PNO3(I)=(PNO3(I)-NO3(NFIRST))/NO3(NDEL)
154       115   CONTINUE
155             DO 125 I=1,NALK,1
156             TALK(I)=(TALK(I)-T(NFIRST))/T(NDEL)
157             PALK(I)=(PALK(I)-ALK(NFIRST))/ALK(NDEL)
158       125   CONTINUE
159             DO 38 I=2,NDH,1
160             T(I)=(T(I-1)+24.0/D)
161       38    CONTINUE
162             DO 335 I=1,NDH,1
163             TI(I)=(T(I)-T(1))/T(NDEL)
164             STXV(I)=(XV(I)-XV(NFIRST))/XV(NDEL)
165             STST(I)=(ST(I)-ST(NFIRST))/ST(NDEL)
166             STNT(I)=(NT(I)-NT(NFIRST))/NT(NDEL)
167             STNH3(I)=(NH3(I)-NH3(NFIRST))/NH3(NDEL)
168       335   CONTINUE
169             TIME(1)=INIT/T(NDEL)
170             DO 205 I=1,IFREQ,1
171             J=2*I-1
172             TIME(J+1)=TIME(J)+ANOX/T(NDEL)
173             TIME(J+2)=TIME(J+1)+AROB/T(NDEL)
174       205   CONTINUE
175             START=START/T(NDEL)+SIZE
176             END=END/T(NDEL)
177             NFR=IFREQ+1
178       45    FORMAT(7E13.5)
179       35    FORMAT()
180             X2=XAX+10.0
181             XPAGE=3.0*X2
182             X3=-2.0*X2
183             CALL PLOTS(0,0,0)
184             CALL FACTOR (0.33)
185             CALL NEWPEN(1)
186             CALL OPMES(24,'PLEASE LOAD P1-BK/I4    ')
187             CALL PAGDEF (-5.0,-6.0,XPAGE,52.0)
188             CALL PLOT(0.0,26.0,-3)
189             CALL NAXIS(0.0,0.0,XAX,0,XSTUK,0.0,1,0.25,2)
190             CALL NAXIS(0.0,YAX,XAX,0,XSTUK,0.0,-1,0.25,2)
191             CALL NAXIS(0.0,0.0,YAX,0,YSTUK,90.0,-1,0.25,2)
```

```
192             CALL NAXIS(XAX,0.0,YAX,0,YSTUK,90.0,1,0.25,2)
193             DO 106 I=1,ITYD,1
194             TYD=T(1)+(I-1)*XAX*T(NDEL)/(ITYD-1)
195             IF(TYD.GT.24.0)TYD=TYD-24.0
196             XVAL=(I-1)*XAX/(ITYD-1.0)-0.5
197             IF(XVAL.LT.0.0) XVAL=0.0
198             CALL NUMBER(XVAL,-1.0,SIZE,TYD,0.0,-1)
199         106 CONTINUE
200             DO 101 I=1,IJ,1
201             YOT=(I-1)*YAX*OT(NDEL)/(IJ-1)
202             YVAL=YOT/OT(NDEL)
203             IF(YOT.LT.9.9) GO TO 301
204             IF(YOT.GT.9.9.AND.YOT.LT.99.9)GO TO 302
205             IF(YOT.GT.99.9)GO TO 303
206         301 CALL NUMBER(-0.5,YVAL,SIZE,YOT,0.0,-1)
207             GO TO 101
208         302 CALL NUMBER(-1.0,YVAL,SIZE,YOT,0.0,-1)
209             GO TO 101
210         303 CALL NUMBER(-1.5,YVAL,SIZE,YOT,0.0,-1)
211         101 CONTINUE
212             CALL SYMBOL(3.5,-2.0,SIZE,'TIME(HOURS)',0.0,11)
213             CALL SYMBOL(-2.0,4.0,SIZE,'OX. UPT. RATE(MGO/L/HR)',90.0,23)
214             DO 215 I=1,NFR,1
215             DO 215 J=1,KJ,1
216             Y=J-1.0
217             IF(TIME(I).GT.XAX) GO TO 215
218             CALL SYMBOL(TIME(I),Y,0.5,13,0.0,-1)
219         215 CONTINUE
220             IF(NAMBA.EQ.1) GO TO 256
221             TEXT=START +2.5
222             CALL SYMBOL(START,YFEED,SIZE,22,90.0,-1)
223             CALL SYMBOL(END,YFEED,SIZE,23,90.0,-2)
224             CALL SYMBOL(TEXT,YWRITE,SIZE,'FEEDING PERIOD',0.0,14)
225         256 CONTINUE
226             DO 255 I=1,IFREQ,2
227             BEGIN=TIME(I)+SIZE
228             CALL SYMBOL(BEGIN,YDOT,SIZE,22,90.0,-1)
229             CALL SYMBOL(TIME(I+1),YDOT,SIZE,23,90.0,-2)
230             X=(TIME(I)+TIME(I+1))/2-0.75
231             CALL SYMBOL(X,Y5,SIZE,'ANOX',0.0,4)
232         255 CONTINUE
233             CALL SYMBOL(0.5,YPLUS,1.0,'OX UPT RATE',0.0,11)
234             CALL SYMBOL(1.0,Y2,SIZE,0,0.0,-1)
235             CALL SYMBOL(1.0,Y4,SIZE,1,0.0,-1)
236             CALL SYMBOL(1.5,Y2,SIZE,'= O2 UPT. RATE',0.0,14)
237             CALL SYMBOL(1.5,Y4,SIZE,'= EQ. O2 UPT. RATE',0.0,18)
238             DO 55 I=1,NOT,1
239             CALL SYMBOL(TOT(I),POT(I),SIZE,0,0.0,-1)
240          55  CONTINUE
241             DO 44 I=1,K,1
242             CALL SYMBOL(TOEQ(I),POEQ(I),SIZE,1,0.0,-1)
243          44  CONTINUE
244             CALL LINE(T,OT,NDH,1,0,0)
245          16 FORMAT(1H ,5X,'T=',F13.5,5X,'OT=',F13.5)
246             CALL PLOT (X2,0.0,-3)
247             CALL NAXIS(0.0,0.0,XAX,0,XSTUK,0.0,1,0.25,2)
248             CALL NAXIS(0.0,YAX,XAX,0,XSTUK,0.0,-1,0.25,2)
249             CALL NAXIS(0.0,0.0,YAX,0,YSTUK,90.0,-1,0.25,2)
250             CALL NAXIS(XAX,0.0,YAX,0,YSTUK,90.0,1,0.25,2)
251             DO 107 I=1,ITYD,1
252             TYD=T(1)+(I-1)*XAX*T(NDEL)/(ITYD-1)
253             IF(TYD.GT.24.0)TYD=TYD-24.0
254             XVAL=(I-1)*XAX/(ITYD-1.0)-0.5
255             IF(XVAL.LT.0.0) XVAL=0.0
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```
256             CALL NUMBER(XVAL,-1.0,SIZE,TYD,0.0,-1)
257       107   CONTINUE
258             IF(NAMBA.EQ.1) GO TO 257
259             CALL SYMBOL(START,YFEED,SIZE,22,90.0,-1)
260             CALL SYMBOL(END,YFEED,SIZE,23,90.0,-2)
261             CALL SYMBOL(TEXT,YWRITE,SIZE,'FEEDING PERIOD',0.0,14)
262       257   CONTINUE
263             DO 102 I=1,IJ,1
264             YST=(I-1)*YAX*ST(NDEL)/(IJ-1)
265             YVAL=YST/ST(NDEL)
266             IF(YST.LT.9.9) GO TO 401
267             IF(YST.GT.9.9.AND.YST.LT.99.9)GO TO 402
268             IF(YST.GT.99.9)GO TO 403
269       401   CALL NUMBER(-0.5,YVAL,SIZE,YST,0.0,-1)
270             GO TO 102
271       402   CALL NUMBER(-1.0,YVAL,SIZE,YST,0.0,-1)
272             GO TO 102
273       403   CALL NUMBER(-1.5,YVAL,SIZE,YST,0.0,-1)
274       102   CONTINUE
275             XAX1=XAX+SIZE
276             DO 111 I=1,3,1
277             YXV=(I-1)*YAX*XV(NDEL)/(IJ-1)
278             YVAL=YXV/XV(NDEL)
279             IF(YXV.LT.9.9) GO TO 501
280             IF(YXV.GT.9.9.AND.YXV.LT.99.9)GO TO 502
281             IF(YXV.GT.99.9)GO TO 503
282       501   CALL NUMBER(XAX1,YVAL,SIZE,YXV,0.0,-1)
283             GO TO 111
284       502   CALL NUMBER(XAX1,YVAL,SIZE,YXV,0.0,-1)
285             GO TO 111
286       503   CALL NUMBER(XAX1,YVAL,SIZE,YXV,0.0,-1)
287       111   CONTINUE
288             CALL SYMBOL(3.5,-2.0,SIZE,'TIME(HOURS)',0.0,11)
289             CALL SYMBOL (-2.0,6.0,SIZE,'COD CONC.(MG/L)',90.0,15)
290             CALL SYMBOL (XVSS,2.0,SIZE,'VSS CONC.(MG/L)',90.0,15)
291             DO 315 I=1,NFR,1
292             DO 315 J=1,KJ,1
293             Y=J-1.0
294             IF(TIME(I).GT.XAX) GO TO 315
295             CALL SYMBOL(TIME(I),Y,0.5,13,0.0,-1)
296       315   CONTINUE
297             DO 355 I=1,IFREQ,2
298             BEGIN=TIME(I)+SIZE
299             CALL SYMBOL(BEGIN,YDOT,SIZE,22,90.0,-1)
300             CALL SYMBOL(TIME(I+1),YDOT,SIZE,23,90.0,-2)
301             X=(TIME(I)+TIME(I+1))/2-0.75
302             CALL SYMBOL(X,Y5,SIZE,'ANOX',0.0,4)
303       355   CONTINUE
304             CALL SYMBOL(0.5,YPLUS,1.0,'COD AND VSS',0.0,11)
305             CALL SYMBOL(1.0,Y4,SIZE,1,0.0,-1)
306             CALL SYMBOL(1.0,Y2,SIZE,2,0.0,-1)
307             CALL SYMBOL(1.5,Y4,SIZE,'= VSS',0.0,5)
308             CALL SYMBOL(1.5,Y2,SIZE,'= COD',0.0,5)
309             CALL SYMBOL(5.5,Y0,SIZE,'EFFLUENT',0.0,8)
310             CALL SYMBOL(5.0,Y1,SIZE,'THEO. EXP.',0.0,10)
311             CALL NUMBER(5.5,Y2,SIZE,ECOD,0.0,-1)
312             CALL NUMBER(8.5,Y2,SIZE,AVCOD,0.0,-1)
313             DO 135 I=1,NXV,1
314             CALL SYMBOL(TXV(I),PXV(I),SIZE,1,0.0,-1)
315       135   CONTINUE
316             DO 145 I=1,NCOD,1
317             CALL SYMBOL(TCOD(I),PCOD(I),SIZE,2,0.0,-1)
318       145   CONTINUE
319             CALL LINE(T,XV,NDH,1,0,0)
```

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320             CALL LINE(T,ST,NDH,1,0,0)
321             CALL PLOT (X2,0.0,-3)
322             CALL NAXIS(0.0,0.0,XAX,0,XSTUK,0.0,1,0.25,2)
323             CALL NAXIS(0.0,YAX,XAX,0,XSTUK,0.0,-1,0.25,2)
324             CALL NAXIS(0.0,0.0,YAX,0,YSTUK,90.0,-1,0.25,2)
325             CALL NAXIS(XAX,0.0,YAX,0,YSTUK,90.0,1,0.25,2)
326             DO 109 I=1,ITYD,1
327             TYD=T(1)+(I-1)*XAX*T(NDEL)/(ITYD-1)
328             IF(TYD.GT.24.0)TYD=TYD-24.0
329             XVAL=(I-1)*XAX/(ITYD-1.0)-0.5
330             IF(XVAL.LT.0.0) XVAL=0.0
331             CALL NUMBER(XVAL,-1.0,SIZE,TYD,0.0,-1)
332      109    CONTINUE
333             IF(NAMBA.EQ.1) GO TO 258
334             CALL SYMBOL(START,YFEED,SIZE,22,90.0,-1)
335             CALL SYMBOL(END,YFEED,SIZE,23,90.0,-2)
336             CALL SYMBOL(TEXT,YWRITE,SIZE,'FEEDING PERIOD',0.0,14)
337      258    CONTINUE
338             DO 104 I=1,IJ,1
339             YNH3=(I-1)*YAX*NH3(NDEL)/(IJ-1)
340             YVAL=YNH3/NH3(NDEL)
341             IF(YNH3.LT.9.9) GO TO 601
342             IF(YNH3.GT.9.9.AND.YNH3.LT.99.9)GO TO 602
343             IF(YNH3.GT.99.9)GO TO 603
344      601    CALL NUMBER(-0.5,YVAL,SIZE,YNH3,0.0,-1)
345             GO TO 104
346      602    CALL NUMBER(-1.0,YVAL,SIZE,YNH3,0.0,-1)
347             GO TO 104
348      603    CALL NUMBER(-1.5,YVAL,SIZE,YNH3,0.0,-1)
349      104    CONTINUE
350             CALL SYMBOL(3.5,-2.0,SIZE,'TIME(HOURS)',0.0,11)
351             CALL SYMBOL(-2.0,6.0,SIZE,'TKN OR NH3(MGN/L)',90.0,17)
352             DO 225 I=1,NFR,1
353             DO 225 J=1,KJ,1
354             Y=J-1.0
355             IF(TIME(I).GT.XAX) GO TO 225
356             CALL SYMBOL(TIME(I),Y,0.5,13,0.0,-1)
357      225    CONTINUE
358             DO 265 I=1,IFREQ,2
359             BEGIN=TIME(I)+SIZE
360             CALL SYMBOL(BEGIN,YDOT,SIZE,22,90.0,-1)
361             CALL SYMBOL(TIME(I+1),YDOT,SIZE,23,90.0,-2)
362             X=(TIME(I)+TIME(I+1))/2-0.75
363             CALL SYMBOL(X,Y5,SIZE,'ANOX',0.0,4)
364      265    CONTINUE
365             CALL SYMBOL(4.0,YPLUS,1.0,'TKN',0.0,3)
366             CALL SYMBOL(1.0,Y2,SIZE,0,0.0,-1)
367             CALL SYMBOL(1.5,Y2,SIZE,'= TKN',0.0,5)
368             CALL SYMBOL(5.5,Y0,SIZE,'EFFLUENT',0.0,8)
369             CALL SYMBOL(5.0,Y1,SIZE,'THEO. EXP.',0.0,10)
370             CALL NUMBER(5.5,Y2,SIZE,ETKN,0.0,1)
371             CALL NUMBER(8.5,Y2,SIZE,AVTKN,0.0,1)
372             DO 155 I=1,NTKN,1
373             CALL SYMBOL(TTKN(I),PTKN(I),SIZE,0,0.0,-1)
374      155    CONTINUE
375             CALL LINE(T,NT,NDH,1,0,0)
376             CALL PLOT (X3,-26.0,-3)
377             CALL NAXIS(0.0,0.0,XAX,0,XSTUK,0.0,1,0.25,2)
378             CALL NAXIS(0.0,YAX,XAX,0,XSTUK,0.0,-1,0.25,2)
379             CALL NAXIS(0.0,0.0,YAX,0,YSTUK,90.0,-1,0.25,2)
380             CALL NAXIS(XAX,0.0,YAX,0,YSTUK,90.0,1,0.25,2)
381             DO 114 I=1,ITYD,1
382             TYD=T(1)+(I-1)*XAX*T(NDEL)/(ITYD-1)
383             IF(TYD.GT.24.0)TYD=TYD-24.0
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384             XVAL=(I-1)*XAX/(ITYD-1.0)-0.5
385             IF(XVAL.LT.0.0) XVAL=0.0
386             CALL NUMBER(XVAL,-1.0,SIZE,TYD,0.0,-1)
387       114   CONTINUE
388             DO 116 I=1,IJ,1
389             YNH3=(I-1)*YAX*NH3(NDEL)/(IJ-1)
390             YVAL=YNH3/NH3(NDEL)
391             IF(YNH3.LT.9.9) GO TO 901
392             IF(YNH3.GT.9.9.AND.YNH3.LT.99.9)GO TO 902
393             IF(YNH3.GT.99.9)GO TO 903
394       901   CALL NUMBER(-0.5,YVAL,SIZE,YNH3,0.0,-1)
395             GO TO 116
396       902   CALL NUMBER(-1.0,YVAL,SIZE,YNH3,0.0,-1)
397             GO TO 116
398       903   CALL NUMBER(-1.5,YVAL,SIZE,YNH3,0.0,-1)
399       116   CONTINUE
400             CALL SYMBOL(3.5,-2.0,SIZE,'TIME(HOURS)',0.0,11)
401             CALL SYMBOL(-2.0,6.0,SIZE,'TKN OR NH3(MGN/L)',90.0,17)
402             DO 226 I=1,NFR,1
403             DO 226 J=1,KJ,1
404             Y=J-1.0
405             IF(TIME(I).GT.XAX) GO TO 226
406             CALL SYMBOL(TIME(I),Y,0.5,13,0.0,-1)
407       226   CONTINUE
408             DO 266 I=1,IFREQ,2
409             BEGIN=TIME(I)+SIZE
410             CALL SYMBOL(BEGIN,YDOT,SIZE,22,90.0,-1)
411             CALL SYMBOL(TIME(I+1),YDOT,SIZE,23,90.0,-2)
412             X=(TIME(I)+TIME(I+1))/2-0.75
413             CALL SYMBOL(X,Y5,SIZE,'ANOX',0.0,4)
414       266   CONTINUE
415             CALL SYMBOL(4.0,YPLUS,1.0,'NH3',0.0,3)
416             CALL SYMBOL(5.5,Y0,SIZE,'EFFLUENT',0.0,8)
417             CALL SYMBOL(5.0,Y1,SIZE,'THEO. EXP.',0.0,10)
418             CALL SYMBOL(1.0,Y2,SIZE,1,0.0,-1)
419             CALL SYMBOL(1.5,Y2,SIZE,'= NH3',0.0,5)
420             CALL NUMBER(5.5,Y2,SIZE,ENH3,0.0,1)
421             CALL NUMBER(8.5,Y2,SIZE,AVNH3,0.0,1)
422             DO 165 I=1,NNH3,1
423             CALL SYMBOL(TNH3(I),PNH3(I),SIZE,1,0.0,-1)
424       165   CONTINUE
425             IF(NAMBA.EQ.1) GO TO 259
426             CALL SYMBOL(START,YFEED,SIZE,22,90.0,-1)
427             CALL SYMBOL(END,YFEED,SIZE,23,90.0,-2)
428             CALL SYMBOL(TEXT,YWRITE,SIZE,'FEEDING PERIOD',0.0,14)
429       259   CONTINUE
430             CALL LINE(T,NH3,NDH,1,0,0)
431             CALL PLOT (X2,0.0,-3)
432             CALL NAXIS(0.0,0.0,XAX,0,XSTUK,0.0,1,0.25,2)
433             CALL NAXIS(0.0,YAX,XAX,0,XSTUK,0.0,-1,0.25,2)
434             CALL NAXIS(0.0,0.0,YAX,0,YSTUK,90.0,-1,0.25,2)
435             CALL NAXIS(XAX,0.0,YAX,0,YSTUK,90.0,1,0.25,2)
436             DO 112 I=1,ITYD,1
437             TYD=T(1)+(I-1)*XAX*T(NDEL)/(ITYD-1)
438             IF(TYD.GT.24.0)TYD=TYD-24.0
439             XVAL=(I-1)*XAX/(ITYD-1.0)-0.5
440             IF(XVAL.LT.0.0) XVAL=0.0
441             CALL NUMBER(XVAL,-1.0,SIZE,TYD,0.0,-1)
442       112   CONTINUE
443             DO 113 I=1,IJ,1
444             YNO3=(I-1)*YAX*NO3(NDEL)/(IJ-1)
445             YVAL=YNO3/NO3(NDEL)
446             IF(YNO3.LT.9.9) GO TO 801
447             IF(YNO3.GT.9.9.AND.YNO3.LT.99.9)GO TO 802
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448             IF(YNO3.GT.99.9)GO TO 803
449       801   CALL NUMBER(-0.5,YVAL,SIZE,YNO3,0.0,-1)
450             GO TO 113
451       802   CALL NUMBER(-1.0,YVAL,SIZE,YNO3,0.0,-1)
452             GO TO 113
453       803   CALL NUMBER(-1.5,YVAL,SIZE,YNO3,0.0,-1)
454       113   CONTINUE
455             CALL SYMBOL(3.5,-2.0,SIZE,'TIME(HOURS)',0.0,11)
456             CALL SYMBOL(-1.5,6.5,SIZE,'NO3(MGN/L)',90.0,10)
457             DO 425 I=1,NFR,1
458             DO 425 J=1,KJ,1
459             Y=J-1.0
460             IF(TIME(I).GT.XAX) GO TO 425
461             CALL SYMBOL(TIME(I),Y,0.5,13,0.0,-1)
462       425   CONTINUE
463             DO 465 I=1,IFREQ,2
464             BEGIN=TIME(I)+SIZE
465             CALL SYMBOL(BEGIN,YDOT,SIZE,22,90.0,-1)
466             CALL SYMBOL(TIME(I+1),YDOT,SIZE,23,90.0,-2)
467             X=(TIME(I)+TIME(I+1))/2-0.75
468             CALL SYMBOL(X,Y5,SIZE,'ANOX',0.0,4)
469       465   CONTINUE
470             CALL SYMBOL(1.5,YPLUS,1.0,'NITRATE',0.0,7)
471             CALL SYMBOL(1.0,Y2,SIZE,0,0.0,-1)
472             CALL SYMBOL(1.5,Y2,SIZE,'= NO3',0.0,5)
473             CALL SYMBOL(5.5,Y0,SIZE,'EFFLUENT',0.0,8)
474             CALL SYMBOL(5.0,Y1,SIZE,'THEO. EXP.',0.0,10)
475             CALL NUMBER(5.5,Y2,SIZE,ENO3,0.0,1)
476             CALL NUMBER(8.5,Y2,SIZE,AVNO3,0.0,1)
477             DO 565 I=1,NNO3,1
478             CALL SYMBOL(TNO3(I),PNO3(I),SIZE,0,0.0,-1)
479       565   CONTINUE
480             IF(NAMBA.EQ.1) GO TO 261
481             CALL SYMBOL(START,YFEED,SIZE,22,90.0,-1)
482             CALL SYMBOL(END,YFEED,SIZE,23,90.0,-2)
483             CALL SYMBOL(TEXT,YWRITE,SIZE,'FEEDING PERIOD',0.0,14)
484       261   CONTINUE
485             CALL LINE(T,NO3,NDH,1,0,0)
486             CALL PLOT (X2,0.0,-3)
487             CALL NAXIS(0.0,0.0,XAX,0,XSTUK,0.0,1,0.25,2)
488             CALL NAXIS(0.0,YAX,XAX,0,XSTUK,0.0,-1,0.25,2)
489             CALL NAXIS(0.0,0.0,YAX,0,YSTUK,90.0,-1,0.25,2)
490             CALL NAXIS(XAX,0.0,YAX,0,YSTUK,90.0,1,0.25,2)
491             DO 108 I=1,ITYD,1
492             TYD=T(1)+(I-1)*XAX*T(NDEL)/(ITYD-1)
493             IF(TYD.GT.24.0)TYD=TYD-24.0
494             XVAL=(I-1)*XAX/(ITYD-1.0)-0.5
495             IF(XVAL.LT.0.0) XVAL=0.0
496             CALL NUMBER(XVAL,-1.0,SIZE,TYD,0.0,-1)
497       108   CONTINUE
498             DO 103 I=1,IJ,1
499             YALK=(I-1)*YAX*ALK(NDEL)/(IJ-1)
500             YVAL=YALK/ALK(NDEL)
501             IF(YALK.LT.9.9) GO TO 701
502             IF(YALK.GT.9.9.AND.YALK.LT.99.9)GO TO 702
503             IF(YALK.GT.99.9)GO TO 703
504       701   CALL NUMBER(-0.5,YVAL,SIZE,YALK,0.0,-1)
505             GO TO 103
506       702   CALL NUMBER(-1.0,YVAL,SIZE,YALK,0.0,-1)
507             GO TO 103
508       703   CALL NUMBER(-1.5,YVAL,SIZE,YALK,0.0,-1)
509       103   CONTINUE
510             CALL SYMBOL(3.5,-2.0,SIZE,'TIME(HOURS)',0.0,11)
511             CALL SYMBOL(-2.0,6.0,SIZE,'ALK(PPM CACO3)',90.0,14)
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512             DO 235 I=1,NFR,1
513             DO 235 J=1,KJ,1
514             Y=J-1.0
515             IF(TIME(I).GT.XAX) GO TO 235
516             CALL SYMBOL(TIME(I),Y,0.5,13,0.0,-1)
517         235 CONTINUE
518             DO 245 I=1,IFREQ,2
519             BEGIN=TIME(I)+SIZE
520             CALL SYMBOL(BEGIN,YDOT,SIZE,22,90.0,-1)
521             CALL SYMBOL(TIME(I+1),YDOT,SIZE,23,90.0,-2)
522             X=(TIME(I)+TIME(I+1))/2-0.75
523             CALL SYMBOL(X,Y5,SIZE,'ANOX',0.0,4)
524         245 CONTINUE
525             CALL SYMBOL(1.5,YPLUS,1.0,'ALKALINITY',0.0,10)
526             CALL SYMBOL(1.5,Y2,SIZE,'= ALK',0.0,5)
527             CALL SYMBOL(1.0,Y2,SIZE,0,0.0,-1)
528             CALL SYMBOL(5.5,Y0,SIZE,'EFFLUENT',0.0,8)
529             CALL SYMBOL(5.0,Y1,SIZE,'THEO. EXP.',0.0,10)
530             CALL NUMBER(5.5,Y2,SIZE,EALK,0.0,-1)
531             CALL NUMBER(8.5,Y2,SIZE,AVALK,0.0,-1)
532             DO 185 I=1,NALK,1
533             CALL SYMBOL(TALK(I),PALK(I),SIZE,0,0.0,-1)
534          185 CONTINUE
535             IF(NAMBA.EQ.1) GO TO 262
536             CALL SYMBOL(START,YFEED,SIZE,22,90.0,-1)
537             CALL SYMBOL(END,YFEED,SIZE,23,90.0,-2)
538             CALL SYMBOL(TEXT,YWRITE,SIZE,'FEEDING PERIOD',0.0,14)
539         262 CONTINUE
540             CALL LINE(T,ALK,NDH,1,0,0)
541             CALL PLOT(0.0,0.0,999)
542             STOP
543             END
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      SUBROUTINE NAXIS(XST,YST,AXLEN,LOG,ANUMBR,ANG,LR,TICK,LINE)
C.... ROUTINE FOR DRAWING AXIS WITHOUT ANNOTATION
C.... (EITHER LOG OR LINEAR)
C....
C.... COMPLIMENTS OF YOUR FRIENDLY CHEM. ENG. DEPARTMENT.
C.... XST,YST = STARTING POSITION
C.... AXLEN   = LENGTH OF AXIS TO BE PLOTTED, CM
C....           (AXLEN MAY BE NEGATIVE)
C.... LOG     = STARTING POSN FOR LOG SCALE, USUALLY 1,
C....           OR = 0 FOR LINEAR SCALE
C.... ANUMBR  = NO. OF LOG CYCLES OR NO. OF TICK INTERVALS
C....           ALONG AXLEN.
C.... ANG     = 0. OR 90. FOR HORIZ. OR VERTICAL AXIS (ONLY)
C.... LR      = LOCATION OF TICK MARKS RELATIVE TO AXIS LINE:
C....           1 FOR CCW, -1 FOR CLOCKWISE.
C.... TICK    = SIZE OF TICK MARK, CM
C.... LINE    = 2 FOR SOLID, 3 FOR BLANK AXIS LINE:
C....           I.E., 3 WILL GIVE TICK MARKS ONLY.
      AXIS=0.
      DX1=0.
      DDX1=0.
      DX2=0.
      DY1=0.
      DDY1=0.
      DY2=0.
      LPOSN=LOG
      IF(AXLEN.NE.0.) GO TO 11
      WRITE(NPR,15)
   15 FORMAT(' WARNING - AXIS LENGTH IN NAXIS ROUTINE IS ZERO.')
      RETURN
   11 DELTA=AXLEN/ANUMBR
      IF(ANG.LT.10.) GO TO 1
      DX1=TICK
      IF(LR.GT.0) DX1=-DX1
      DDX1=DX1
      GO TO 2
    1 DY1=TICK
      IF(LR.LT.0) DY1=-DY1
      DDY1=DY1
C.... START AXIS
    2 CALL PLOT(XST,YST,3)
      X=XST
      Y=YST
    3 IF(LOG.EQ.0) GO TO 4
C.... SET UP LOG SCALE
      DELTA=(ALOG10(LPOSN+1)-ALOG10(LPOSN))*AXLEN/ANUMBR
      LPOSN=LPOSN+1
      IF(LPOSN.EQ.10) LPOSN=1
      DX1=DDX1
      DY1=DDY1
      IF(LPOSN.NE.2) GO TO 4
      IF(TICK.GT.(.1*AXLEN)) GO TO 4
      DX1=2*DX1
      DY1=2*DY1
    4 IF(ANG.LT.10.)DX2=DELTA
      IF(ANG.GT.10.) DY2=DELTA
      AXIS=AXIS+ABS(DELTA)
      CALL PLOT(X+DX1,Y+DY1,2)
      CALL PLOT(X,Y,3)
      IF(AXIS.GT.ABS(AXLEN)) GO TO 5
      X=X+DX2
      Y=Y+DY2
      CALL PLOT(X,Y,LINE)
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64              GO TO 3
65        5     IF(ANG.LT.10.) X=XST+AXLEN
66              IF(ANG.GT.10.) Y=YST+AXLEN
67              CALL PLOT(X,Y,LINE)
68              RETURN
69              END
```

APPENDIX B

MASS BALANCE OF A PREDENITRIFICATION SYSTEM

B.1 General considerations of nitrogen and COD mass balances

It is possible to perform nitrogen and COD mass balances on the series system in Fig. 3.1 operated under constant flow and load conditions.

The nitrogen mass balance can be used to check on the mixed liquor and underflow recycle pump ratings respectively, subject to inaccuracies related to (1) nitrate, TKN and VSS measurement and (2) possible denitrification in the settler that is unaccounted for. The formulation of nitrogen balance is given in Section B.3.

A prerequisite to a satisfactory COD mass balance is an accurate determination of both the system nitrification and the system denitrification. In addition, errors related to the oxygen uptake rate test will ultimately manifest themselves in the COD mass balance. The formulation of COD balance is given in Section B.4.

In order to dampen any possible irregularities, the average values of the measured parameters for each batch of sewage disregarding outliers were used. The following parameters were measured:

CODIN = Influent total COD concentration [mg COD.ℓ^{-1}]
CODOUT = Effluent total COD concentration [mg COD.ℓ^{-1}]
TKNIN = Influent total TKN concentration [mg N.ℓ^{-1}]
TKNOUT = Effluent total TKN concentration [mg N.ℓ^{-1}]

VSS = Volatile suspended solids concentration [mg VSS.ℓ^{-1}]

P = COD equivalent content of the sludge [mg COD.mg VSS^{-1}]

a = Mixed liquor recycle ratio (see Fig. 3.1)

s = Underflow recycle ratio (see Fig. 3.1)

Q = Volumetric influent flow rate [$\ell.d^{-1}$]

q = Volumetric wastage flow rate [$\ell.d^{-1}$]

OUR_1 = Oxygen uptake rate in A1 (see Fig. 3.1) [mg O.$\ell^{-1}.h^{-1}$]

OUR_2 = Oxygen uptake rate in A2 (see Fig. 3.1) [mg O.$\ell^{-1}.h^{-1}$]

NO_3AN = Anoxic reactor nitrate concentration [mg NO_3-N.ℓ^{-1}]

NO_3A1 = Nitrate concentration in A1 (see Fig. 3.1) [mg NO_3-N.ℓ^{-1}]

NO_3A2 = Nitrate concentration in A2 (see Fig. 3.1) [mg NO_3-N.ℓ^{-1}]

NO_3EFF = Effluent nitrate concentration [mg NO_3-N.ℓ^{-1}]

OXFEED = Dissolved oxygen concentration in the feed [mg O.ℓ^{-1}]

B.2 The COD equivalent content of the sludge

B.2a Mean value for the COD equivalent content of the sludge

The COD equivalent content of the sludge, P, has been measured regularly by performing the COD test on a known amount of sludge and proved to be 1,54 ± 0,01 [mg COD.mg VSS^{-1}] at 14°C, pH = 7,2 and R_s= 15[d] (see Fig. 2.10). Hence the mean value of the COD content of the sludge, P = 1,54 [mg COD.mg VSS^{-1}], has been assumed in all the calculations and simulations involving a nitrification-denitrification system at 14°C, pH = 7,2 and R_s= 15[d].

B.2b Variations in P for different batches of the same sewage source

Experimentally measured values of the COD/VSS ratios at 14°C, pH = 7,2 and R_s= 15[d] are plotted in Fig. 2.11 for each batch of sewage, and the mean COD/VSS ratio for each batch, disregarding any outliers is indicated. From Fig. 2.11 it seems that the VSS/COD ratio varies for different batches of the same sewage source (Zeekoevlei outfall). This can be explained if it is hypothesized that the COD/VSS ratio *inter alia* depends on the sewage characteristics; variation in characteristics of different batches of the same sewage source may be explained if it is accepted that the industrial fraction in some batches varied.

B.3 Nitrogen mass balance formulation

B.3a Nitrate mass balance on the anoxic reactor

Nitrate mass balance can be performed on the anoxic reactor in Fig. 3.1, provided nitrate is always present in the anoxic reactor. Assuming there is no nitrate in the influent waste flow, the system nitrogen removal is given by the following nitrate mass balance:

$$DENIT = Q.[a.NO_3A2+s.(NO_3EFF+NO_3A2)/2-(a+s+1).NO_3AN][mgNO_3\text{-}N.d^{-1}]$$

where

$(NO_3EFF+NO_3A2)/2$ = estimated nitrate concentration in the underflow recycle [mg $NO_3.\ell^{-1}$]

B.3b Heterotrophic nitrogenous nutrient requirement

Heterotrophic nitrogenous nutrient requirement is based on the measured VSS value and is given by

$$NSL = f_n.X_v.q \ [mg\ N.d^{-1}]$$

where

NSL = Nitrogen incorporated in the sludge [mg $N.d^{-1}$]

f_n = mass fraction of nitrogen in the organic sludge = 0,1 [mg $N.mgVSS^{-1}$]

X_v = Volatile suspended solids concentration [mg $VSS.\ell^{-1}$]

B.3c System nitrogen balance

The system nitrogen balance is given by:

$$Q.TKNIN = Q.TKNOUT + NSL + Q.NO_3EFF + DENIT.$$

Hence the nitrogen mass balance (recovery) is given by

$$NBAL = NRECOV = (Q.TKNOUT + NSL + Q.NO_3EFF + DENIT)/(Q.TKNIN)$$

B.4 COD mass balance formulation

B.4a COD utilization due to denitrification

Accepting that denitrification of 1 mg NO_3-N is equivalent to the utilization of 2,86 mg COD [Section 2.3.1], the COD utilization due to denitrification, CODDEN, is given by

$$CODDEN = 2,86\ [Q.TKNIN-(Q.TKNOUT + Q.NO_3EFF + NSL)][mg\ COD.d^{-1}]$$

B.4b Heterotrophic carbonaceous oxygen requirements

Accepting that nitrification of 1 mg N requires 4,57 mg O [Section 2.1.3], the heterotrophic carbonaceous oxygen requirements

may be calculated by subtracting from the total oxygen requirements the amount of oxygen that is needed for nitrification i.e.

$$COR = [OUR_1.24.V_{A1}+OUR_2.24.V_{A2}]-[Q.TKNIN-(Q.TKNOUT+NSL)].4,57[mg\ O.d^{-1}]$$

where

V_{A1} = Volume of A1 [ℓ]
V_{A2} = Volume of A2 [ℓ]
COR = Carbonaceous oxygen requirements [mg $O.d^{-1}$]

B.4c COD removal by sludge wastage

The COD removed with the wasted sludge is given by

$$CODSL = P.q.X_v\ [mg\ COD.d^{-1}]$$

B.4d Dissolved oxygen effects of recycle streams

The mixed liquor and the underflow recycle stream, respectively, introduce dissolved oxygen into the anoxic reactor. The dissolved oxygen concentration in the aerobic reactor was maintained at about 2 [mg $O.ℓ^{-1}$] in order to ensure efficient nitrification. This means that the mixed liquor 'a' recycle stream will have a dissolved oxygen concentration of about 2 [mg $O.ℓ^{-1}$]. Because the dissolved oxygen in the settler is lower than that in the aerobic reactor, an approximate dissolved oxygen concentration of 1,5 [mg $O.ℓ^{-1}$] has been assumed for each of the recycle streams entering the anoxic reactor. Hence an estimation of the total dissolved oxygen returning with the recycle streams to the anoxic reactor is given by:

$$RETOX = Q.(a+s).1,5\ [mg\ COD.d^{-1}]$$

B.4e Dissolved oxygen effects of feed

The feed is an additional source of dissolved oxygen, considering that it is very well aerated prior to its introduction into the anoxic reactor and is thereafter kept in good contact with oxygen in the air due to the continuous stirring. (The influent is stirred in order to affect an homogenous feed). The amount of oxygen introduced by the feed is given by Q.OXFEED where OXFEED is the dissolved oxygen concentration in the feed as [mg $O.ℓ^{-1}$].

B.4f Errors inherent in the oxygen uptake rate test

The oxygen uptake rate test was done by raising the dissolved oxygen concentration to a high value (6 [mg $O.\ell^{-1}$]), stopping aeration and thereafter monitoring the rate of oxygen uptake by the organisms. Inherent in the oxygen uptake rate test are two effects that tend to act in a compensatory fashion with each other:

(1) An error made in oxygen uptake rate measurement is proportional to the dissolved oxygen concentration gradient (i.e. the difference between the reactor dissolved oxygen concentration and the influent dissolved oxygen concentration to the reactor).

(2) An error with the opposite effect is the continuous penetration and dissolution of atmospheric oxygen into the mixed liquor during the oxygen uptake rate test.

In Appendix C.1 a relationship allowing for these two effects is developed and in Appendix C.2 it becomes apparent that for the system depicted in Fig. 3.1 these two effects are of the same order of magnitude and opposed to each other, hence they are ultimately ignored in the COD mass balance.

B.4g System COD balance

In view of Section B.4 (a to f) the COD system mass balance is given by

$$Q.CODIN = CODDEN+COR+CODSL+Q.CODOUT+RETOX+Q.OXFEED \text{ [mg COD.d}^{-1}\text{]}$$

where

CODIN = Influent total COD concentration [mg $COD.\ell^{-1}$]
CODOUT = Effluent total COD concentration [mg $COD.\ell^{-1}$]

Hence the COD mass balance (recovery) is given by

$$CODREC = (CODDEN+COR+CODSL+Q.CODOUT+RETOX+Q.OXFEED)/(Q.CODIN).$$

B.5 Calculation of mass balance on the predenitrification system given by Fig. 3.1

In view of Appendix B (1 to 4), a Fortran program (program B.1) has been written to calculate nitrogen and COD mass balances as follows:

PROGRAM B.1

```
C      THIS PROGRAM CALCULATES NITROGEN AND COD MASS BALANCES ON
C      THE PREDENITRIFICATION SYSTEM GIVEN IN FIGURE 3.1
C
C*************************************************************************
C      THE MEANING OF THE INPUT PARAMETERS IS AS FOLLOWS:
C
C     CODIN=INFLUENT COD CONCENTRATION
C     CODOUT=EFFLUENT COD CONCENTRATION
C     TKNIN=INFLUENT TKN CONCENTRATION
C     TKNOUT=EFFLUENT TKN CONCENTRATION
C     VSS=VOLATILE SUSPENDED SOLIDS CONCENTRATION
C     P=COD/VSS RATIO (THE COD CONTENT OF THE SLUDGE)
C     A=MIXED LIQUOR RECYCLE RATIO
C     S=UNDERFLOW RECYCLE RATIO
C     Q=INFLUENT FLOW RATE
C     QQ=WASTAGE FLOW RATE
C     OUR1=OXYGEN UPTAKE RATE IN THE FIRST AEROBIC REACTOR - A1
C     OUR2=OXYGEN UPTAKE RATE IN THE SECOND AEROBIC REACTOR - A2
C     NO3AN=NITRATE CONCENTRATION IN THE ANOXIC REACTOR - AN
C     NO3A2=NITRATE CONCENTRATION IN A2
C     NO3EFF=EFFLUENT NITRATE CONCENTRATION
C     OXFEED=DISSOLVED OXYGEN CONCENTRATION IN THE INFLUENT FEED
C
C*************************************************************************
C
C      THE PROGRAM OUTPUT VARIABLES ARE:
C
C      DATE=DAY AT WHICH MASS BALANCE WAS PERFORMED
C      MONTH=MONTH AT WHICH MASS BALANCE WAS PERFORMED
C      CODIN=INFLUENT COD CONCENTRATION
C      CODOUT=EFFLUENT COD CONCENTRATION
C      TKNIN=INFLUENT TKN CONCENTRATION
C      TKNOUT=EFFLUENT TKN CONCENTRATION
C      OUR1=OXYGEN UPTAKE RATE IN THE FIRST AEROBIC REACTOR - A1
C      OUR2=OXYGEN UPTAKE RATE IN THE SECOND AEROBIC REACTOR - A2
C      NO3AN=NITRATE CONCENTRATION IN THE ANOXIC REACTOR - AN
C      NO3A2=NITRATE CONCENTRATION IN THE SECOND AEROBIC REACTOR
C      NO3EFF=EFFLUENT NITRATE CONCENTATION
C      DNIT=NITROGEN REMOVED BY THE SYSTEM
C      NRECOV=NITROGEN RECOVERY (NITROGEN MASS BALANCE)
C      CODREC=COD RECOVERY (COD MASS BALANCE)
C*************************************************************************
      REAL NO3AN,NO3A2,NO3EFF,NSL,NRECOV
      INTEGER DATE
      READ 104,N
  104 FORMAT(I2)
      PRINT 105
  105 FORMAT(1H ,4X,'DATE',4X,'CODIN',4X,'CODOUT',4X,'TKNIN',4X,'TKNOUT'
     %,4X,'OUR1',4X,'OUR2',4X,'NO3AN',4X,'NO3A2',4X,'NO3EFF',4X,'NRECOV'
     %,4X,'CODBAL',4X,'DNIT',/,1H ,4X,4('-'),4X,5('-'),4X,6('-'),4X,5('-
     %'),4X,6('-'),4X,4('-'),4X,4('-'),4X,5('-'),4X,5('-'),4X,6('-'),4X,
     %6('-'),4X,6('-'),4X,4('-'))
      DO 10 I=1,N
      READ101,CODIN,CODOUT,TKNIN,TKNOUT,VSS,P,A,S,Q,QQ,OUR1,OUR2,NO3AN
      READ101,NO3A2,NO3EFF,OXFEED
      READ 103,DATE,MONTH
  103 FORMAT(I2,I2)
  101 FORMAT()
      TNIN=Q*TKNIN
      NSL=0.1*VSS*QQ
      TNOUT=Q*TKNOUT
      DENIT=Q*(A*NO3A2+S*(NO3EFF+NO3A2)/2-(A+S+1.0)*NO3AN)
      TNO3EF=NO3EFF*Q
```

```
64            NRECOV=100.*(TNOUT+TNO3EF+DENIT+NSL)/TNIN
65            RDENIT=TNIN-(TNOUT+TNO3EF+NSL)
66            TCODIN=CODIN*Q
67            CODDEN=RDENIT*2.86
68            CODOUR=OUR1*24.*2.5+OUR2*24.*4.5
69            TOTNIT=(TNO3EF+RDENIT)*4.57
70            CODSL=P*QQ*VSS
71            TCODEF=CODOUT*Q
72            RETOX=Q*(A+S)*1.5
73            CODREC=(CODDEN+CODOUR-TOTNIT+CODSL+TCODEF+RETOX+Q*OXFEED)
74           %*100./TCODIN
75            DNIT=DENIT/Q
76          10 PRINT 100,DATE,MONTH,CODIN,CODOUT,TKNIN,TKNOUT,OUR1,OUR2,NO3AN,NO3
77            %A2,NO3EFF,NRECOV,CODREC,DNIT
78         100 FORMAT(1H ,4X,I2,I2,4X,F5.1,4X,F6.1,4X,F5.1,4X,F6.1,4X,F4.1,4X,F4.
79            %1,4X,F5.1,4X,F5.1,4X,F6.1,4X,F6.2,4X,F6.2,4X,F4.1)
80            END
```

The system depicted in Fig. 3.1 was run under constant flow and load conditions until satisfactory* nitrogen *and* COD mass balances were obtained using *average values* of the measured parameters *for each batch* of sewage. A summary of program B.1 output for all sewage batches is given in Table 3.1 [see Section 3.2.1].

---

*Satisfactory nitrogen and COD mass balances are defined as above 95% and 90% recovery respectively.

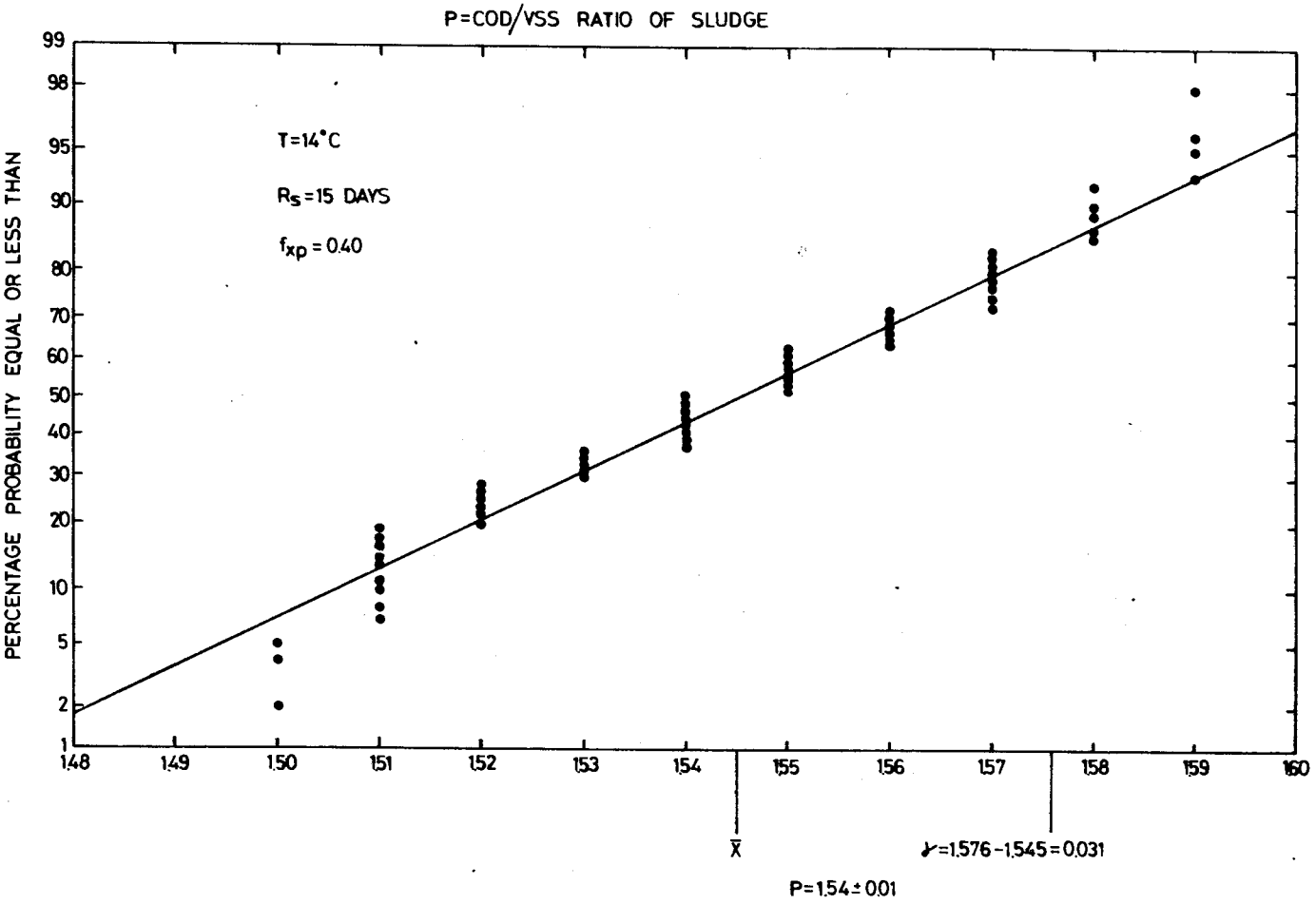

Fig.2.10: Mean value for P (COD content of the sludge) from a statistical analysis.

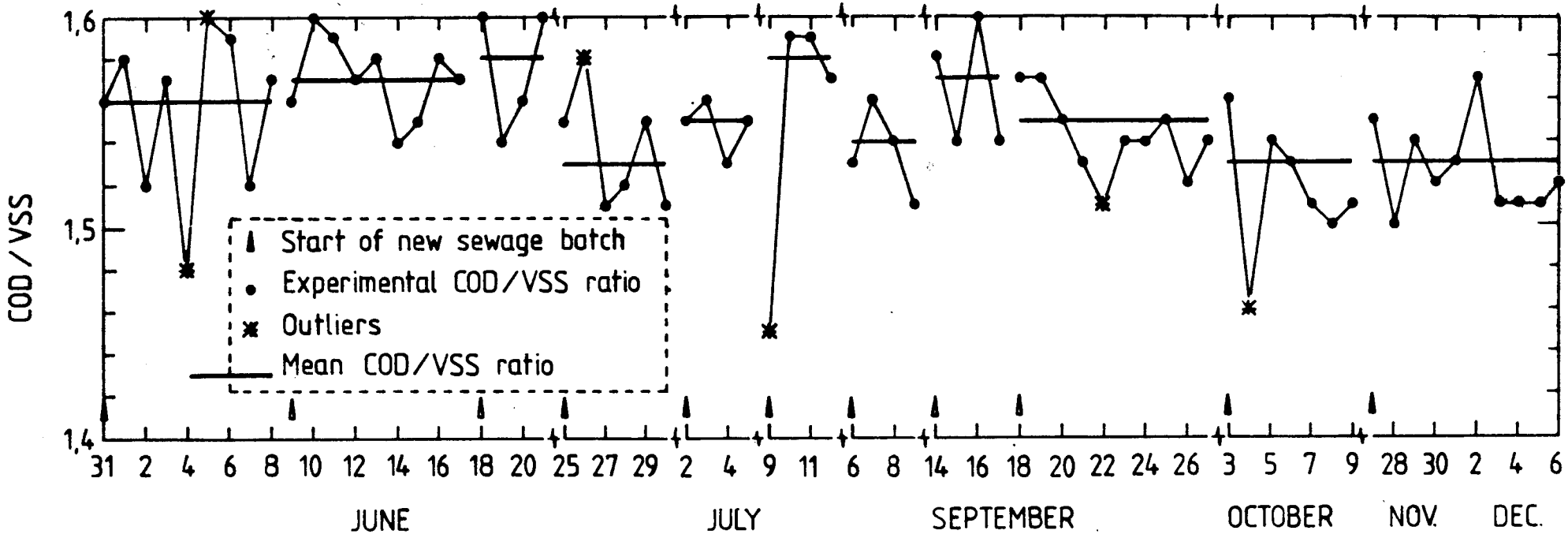

Fig.2.11 Variations in the experimentally measured COD/VSS ratio for different batches of Zeekoevlei sewage outfall at 14°C, pH = 7,2, R_s = 15 days.

APPENDIX C

C.1 A critical review of the oxygen uptake rate test

Successful application of oxygen uptake rate measurements depends on the ability to identify and quantify any errors inherent to the test.

The observed oxygen uptake rate $[(dD/dt)_{obs}]$ is the algebraic sum of (1) the rate of oxygen utilization by the organisms $[(dD/dt)_u]$, (2) the net rate of change in the oxygen concentration due to the dissolved oxygen concentration gradient (the difference in the dissolved oxygen (DO) concentrations of the influent to the reactor and the effluent from the reactor respectively), $[(dD/dt)_{IE}]$, and (3) the reaeration rate $[(dD/dt)_r]$, i.e.

$$(dD/dt)_{obs} = (dD/dt)_u + (dD/dt)_{IE} + (dD/dt)_r \qquad (a)$$

C.1a Effect of (DO) concentration gradient

If the mixed liquor entering the reactor has a DO concentration different from that leaving the reactor (as will, usually, be the case), then there will be a net change in the DO concentration due to this difference. This can be expressed as

$$r_{IE} = -(dD/dt)_{IE} = [Q_a.(D_i-D)/(24\ V)] \qquad (b)$$

where

D = DO concentration in the reactor [mg $O.\ell^{-1}$]

D_i = DO concentration in the influent mixed liquor to the reactor [mg $O.\ell^{-1}$]

Q_a = Actual flow rate (including any recycles) to the reactor [$\ell.d^{-1}$]

$r_{IE} = -(dD/dt)_{IE}$ = Change in oxygen uptake rate due to the difference in DO concentrations of the influent to the reactor and the effluent from the reactor, respectively. (Negative sign indicates disappearance of oxygen). (Δ[mg $O.\ell^{-1}.h^{-1}$])

C.1b Effect of reaeration

Because the mixed liquor is not saturated with respect to DO, there is a certain rate of reaeration, r_r, which depends upon

(1) The free surface/volume ratio.

(2) The renewal rate of the free surface, i.e. the overall mixing intensity. The overall mixing intensity is mainly governed by the intensity of stirring and shear stress. The shear stress is the 'drag' effect caused by the introduction of influent to the mixed liquor in the reactor, i.e.

$$r_r = (dD/dt)_r = K_a.(A_s/V) + r_t \qquad (c)$$

where

K_a = Transfer coefficient [mg $O.h^{-1}.m^{-2}$]

A_s = Free surface area [m^2]

V = Reactor volume [ℓ]

r_t = Reaeration via the opening in the U-tube preceding the reactor under consideration [mg $O.\ell^{-1}.h^{-1}$].

It must be noted that r_r is specific to a certain reactor under certain conditions of flow and mixing and must therefore be determined experimentally for each particular case. Also the value of K_a need not be directly applicable for scale up purposes and is specific to the particular influent waste under consideration. Hence r_r is measured by substituting tap water for mixed liquor in the specific reactor (with its specific mixer), purging the water with nitrogen and thereafter monitoring the increase in DO concentration with time (rate of reaeration), keeping all flow streams operational at their respective experimental values.

In most practical cases r_r is usually so small that it has very little effect, but in bench scale units the ratio A_s/V sometimes is so high that the effect of reaeration becomes significant, especially when the oxygen uptake rate is low and the reactor is intensely stirred.

C.2 Determination of r_u

Substituting into Eq. (a) for $(dD/dt)_{IE}$ and $(dD/dt)_r$ from Eqs. (b) and (c) respectively, the observed rate of change of DO concentration, $r_{obs} = -(dD/dt)_{obs}$, can be written:

$$-(dD/dt)_{obs} = r_{obs} - r_u + r_{IE} - r_r = -(dD/dt)_v-(dD/dt)_{IE}-(dD/dt)_r$$

hence,

$$r_u = r_{obs} + (dD/dt)_{IE} + (dD/dt)_r$$

or

$$r_u = r_{obs} -[Q_a(D_i-D)/(24.V)] + r_r \qquad (d)$$

The rate of oxygen utilization by the organisms is estimated by adjusting the observed oxygen uptake rate according to Eq. (d). The value of r_u is now evaluated in turn for (I) the predenitrification system given in Fig. 3.1, and (II) for the completely mixed single reactor process given in Fig. 3.3.

(I) Considering the system in Fig. 3.1, the reaeration rates r_{rx} for any reactor x have been measured experimentally at 14°C as described in Section C.1(b) and were found to be:

$r_{rA1} = 7,5$ [mg $O.\ell^{-1}.h^{-1}$]

$r_{rA2} = 2,5$ [mg $O.\ell^{-1}.h^{-1}$]

(subscripts A1 and A2 refer to aerobic reactors A1 and A2, respectively).

i.e. $r_r = \Sigma r_{rx} = 7,5 + 2,5 = 10,0$ [mg $O.\ell^{-1}.h^{-1}$]

For the system in Fig. 3.1 with

$V_{A1} = 2,5$ [ℓ]

$V_{A2} = 4,5$ [ℓ]

$(a+s+1) = 7$,

and assuming an average reactor DO concentration during the oxygen utilization rate test to be $D_o = 4$ [mg $O.\ell^{-1}$] (this seems a fair assumption considering that the oxygen uptake rate test is carried out between an upper DO concentration level of about 6 [mg $O.\ell^{-1}$] and a lower DO concentration level of about 2 [mg $O.\ell^{-1}$]),

$$r_{IE_{A1}} = -[Q_a(D_o-D_i)/(24.V)]_{A1} = -17,2.7.(4-0)/(24.2,5) = -8,0 [mg\,0.\ell^{-1}.h^{-1}]$$

$$r_{IE_{A2}} = -[Q_a(D_o-D_i)/(24.V)]_{A2} = -17,2.7.(4-2)/(24.4,5) = -2,2 [mg\,0.\ell^{-1}.h^{-1}]$$

i.e.

$$r_{IE} = \Sigma r_{IE_x} = -8,0 + (-2,2) = -10,2 \ [mg\ 0.\ell^{-1}.h^{-1}]$$

If r_u is calculated by using Eq.(d), it becomes apparent that for the system in Fig. 3.1, r_{IE} and r_r tend to cancel each other out. It therefore becomes unnecessary to consider these effects and hence they are ignored.

(II) Considering the single reactor system in Fig.3.3(that was sequentially subjected to anoxic and aerobic conditions), i.e.

$V = 15 \ [\ell]$

$Q_a = Q.(s+1) = 30.(2+1) = 90 \ [\ell.d^{-1}]$.

Experiment (as described in Section C.1b) gives

$r_r \simeq 0,2 \ [mg\ 0.\ell^{-1}.h^{-1}]$.

In view of the very small magnitude of r_r, the effect of the reaeration rate on r_u is ignored in the completely mixed single reactor (CMSR) system.

It is quite meaningless to attempt an accurate evaluation of the reactor's DO concentration and the reactor's inlet DO concentration during the oxygen utilization test. The main reason for that is the continuous underflow recycle (from the settler) with its varying DO concentration, directly into the reactor during the oxygen utilization rate (O.U.R.) test. A very rough indication of the magnitude of r_{IE} can be given if an average reactor DO concentration during the O.U.R. test is accepted as $D_o \simeq 4 \ [mg\ 0.\ell^{-1}]$ and an average underflow recycle DO concentration is assumed to be $2 \ [mg\ 0.\ell^{-1}]$, in which event r_{IE} will be given by

$$r_{IE} = -[Q_a(D_o-D_i)/(24\ V)] \simeq -[90.(4-2)/(24.15)] = -0,5 \ [mg\ 0.\ell^{-1}].$$

The uncertainty associated with the estimation of r_{IE} makes it difficult to accurately determine the value of r_u when using Eq.(d). Fortunately the magnitude of r_{IE} is very small and is not too far

away from the magnitude of r_r, except that it affects r_u in the opposite fashion to the way r_r affects r_u. Hence it becomes unnecessary to consider the effects of r_r and r_{IE} in the CMSR system and they are consequently ignored.